2012-09

Analysis of the Inshore California Current System Off Central California Using Naval Oceanographic Office Survey Data from 1997 to 2002

Penrose, Luke W.

Monterey, California. Naval Postgraduate School

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

ANALYSIS OF THE INSHORE CALIFORNIA CURRENT SYSTEM OFF CENTRAL CALIFORNIA USING NAVAL OCEANOGRAPHIC OFFICE SURVEY DATA FROM 1997 TO 2002

by

Luke W. Penrose

September 2012

Thesis Advisor: Curtis A. Collins
Second Reader: Tetyana Margolina

Approved for public release, distribution is unlimited

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.			
1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** September 2012	**3. REPORT TYPE AND DATES COVERED** Master's Thesis	
4. TITLE AND SUBTITLE Analysis of the Inshore California Current System Off Central California Using Naval Oceanographic Office Survey Data from 1997 to 2002			**5. FUNDING NUMBERS**
6. AUTHOR(S) Luke W. Penrose			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number ______N/A______.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release, distribution is unlimited			**12b. DISTRIBUTION CODE** A

13. ABSTRACT (maximum 200 words)

Hydrographic measurements from ten Naval Oceanographic Office cruises during 1997–2002 were analyzed. Data included CTD soundings to 1000 dbar and shipboard ADCP current measurements. Water properties (pressure, spiciness, acceleration potential) were optimally interpolated onto the 26.0 kg/m^3 and 26.8 kg/m^3 isopycnal. Steric heights for the sea surface relative to 1000 dbar are compared with satellite altimeter measurements.

Mean fields and their variability were described. The 26.8 kg/m^3 isopycnal shoaled offshore, forming a ridge about 100 km from shore that divided low offshore and high inshore spiciness. The 26.0 kg/m^3 isopycnal sloped upward toward the coast due to upwelling. Acceleration potential on the 26.0 kg/m^3 isopycnal showed persistent poleward inshore flow for all cruises and with indication of weak circulation of offshore waters toward the coast to the north of Monterey Bay and weak circulation of inshore waters to the west near Point Sur. The 26.8 kg/m^3 isopycnal showed a similar pattern but with stronger poleward flow along the coast.

Data from individual cruises provided details on the variability of the mean fields. The most robust properties were the spiciness distributions. A distinct gradient of spiciness occurred near 123°12′W on both isopycnals, separating high spiciness inshore water from lower spiciness offshore.

14. SUBJECT TERMS California Current System, Central California, CalCOFI, Monterey Bay, Naval Oceanographic Office physical oceanography surveys, isentropic analysis			**15. NUMBER OF PAGES** 167
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

ANALYSIS OF THE INSHORE CALIFORNIA CURRENT SYSTEM OFF CENTRAL CALIFORNIA USING NAVAL OCEANOGRAPHIC OFFICE SURVEY DATA FROM 1997 TO 2002

Luke W. Penrose
Lieutenant, United States Navy
B.S., United States Naval Academy, 2006

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN PHYSICAL OCEANOGRAPHY

from the

NAVAL POSTGRADUATE SCHOOL
September 2012

Author: Luke W. Penrose

Approved by: Curtis A. Collins
Thesis Advisor

Tetyana Margolina
Thesis Co-Advisor

Mary L. Batteen
Chair, Department of Oceanography

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

Hydrographic measurements from ten Naval Oceanographic Office cruises during 1997-2002 were analyzed. Data included CTD soundings to 1000 dbar and shipboard ADCP current measurements. Water properties (pressure, spiciness, acceleration potential) were optimally interpolated onto the 26.0 kg/m^3 and 26.8 kg/m^3 isopycnal. Steric heights for the sea surface relative to 1000 dbar are compared with satellite altimeter measurements.

Mean fields and their variability were described. The 26.8 kg/m^3 isopycnal shoaled offshore, forming a ridge about 100 km from shore that divided low offshore and high inshore spiciness. The 26.0 kg/m^3 isopycnal sloped upward toward the coast due to upwelling. Acceleration potential on the 26.0 kg/m^3 isopycnal showed persistent poleward inshore flow for all cruises and with indication of weak circulation of offshore waters toward the coast to the north of Monterey Bay and weak circulation of inshore waters to the west near Point Sur. The 26.8 kg/m^3 isopycnal showed a similar pattern but with stronger poleward flow along the coast.

Data from individual cruises provided details on the variability of the mean fields. The most robust properties were the spiciness distributions. A distinct gradient of spiciness occurred near 123°12´W on both isopycnals, separating high spiciness inshore water from lower spiciness offshore.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

I would like to acknowledge Mr. Paul Taylor and Mr. Gordon Wilkes from the Naval Oceanographic Office. These two men were responsible for organizing the NAVO cruises for which this thesis analyzed, and their utilization of the Naval Postgraduate School for assistance with these surveys allowed for my research to be possible.

Without my thesis advisors, Dr. Curtis Collins, and Research Associate Tetyana Margolina, the completion of my thesis would not have been possible. I learned immensely from the guidance and experience of Dr. Collins and am truly thankful. I enjoyed learning from you and appreciate your patience and willingness to serve as my advisor (along with the occasional baseball discussion). Tetyana, you started this research prior to my arrival at NPS. I thank you for the constant help with MATLAB® and always answering every question I had thoroughly and promptly and the accessibility you provided me to your prior research.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

The focus of this thesis will be to analyze a data set consisting of ten Naval Oceanographic Office (NAVO) surveys of oceanographic conditions off the coast of central California. Each survey took about two weeks and was carried out during the following periods: February 1997, September 1997, May 1998, November 1998, January 1999, November 1999, September 2000, March 2001, December 2001, and November 2002. The purpose of these surveys was to provide an improved ocean data base for a region where a variety of training activities were conducted.

A. SURVEY OVERVIEW

All surveys were taken within the California Current System (CCS). Ocean observations for the California Current System have been obtained by the California Cooperative Oceanic Fisheries Investigations (CalCOFI) since its establishment in 1949. An extensive analysis of observations for 1950 to 1978 was completed by Lynn and Simpson (1987). Their results showed that the CCS contained three distinct domains: oceanic, coastal, and a transition zone between the oceanic and coastal domains. Within these domains there exists (varying seasonally and yearly) the equatorward-flowing California Current (CC), the poleward Inshore Countercurrent (IC), and the poleward California Undercurrent (CU). The water properties of the CCS are derived from four water masses, Pacific Subarctic, North Pacific Central, Equatorial Pacific, and coastally upwelled water

The 1997 to 2002 NAVO surveys included hydrographic (CTD) measurements and vessel mounted ADCP measurements and were carried out using CalCOFI protocols. These NAVO surveys (though strictly neither synoptic nor mesoscale) can resolve circulation patterns and water mass properties and, through comparison with early CalCOFI data, document changes that occur over a half-century period.

B. LYNN AND SIMPSON (1987) ANALYSIS OF CCS HYDROGRAPHIC DATA

As mentioned above, Lynn and Simpson (1987) have described physical characteristics of the CCS as well as their seasonal variability. The equatorward flowing CC is the eastern limit of the large-scale anti-cyclonic subtropical gyre of the North Pacific Ocean, and is a surface current. Its average speed off of the California coast is 25 cm/s. Bordering the California Current system to the west is the Subarctic Frontal Zone, which is typically located about 850–900 kilometers (km) from the coast.

Near to the coast, the poleward IC exists as a seasonal change in the direction of shallow inshore flow. This poleward flow typically exists throughout the fall and winter, extending to 150 km offshore. North of Point Conception this current is sometimes referred to as the Davidson Current (DC).

The CU is considered to originate in the eastern equatorial Pacific and flow poleward along the coast of North America (Sverdrup and Fleming 1941). The CU shows considerable seasonal variability in its position, strength, and core depth. The CU and CC form an inshore cyclonic gyre which is marked by both Ekman pumping and coastal upwelling.

Observations analyzed by Lynn and Simpson began in 1949, using a regular grid of stations extending to 700 kilometers offshore from San Francisco to southern Baja California. Until 1964, Nansen casts were the standard sampling method. After 1964, salinity-temperature-depth (STD) and conductivity-temperature-depth (CTD) casts were taken in conjunction with a Nansen cast or water bottle samples, for purposes of calibration.

To resolve temporal variability Lynn and Simpson (1987) fit harmonic curves composed of annual and semi-annual components to observations at each station using least squares regression analysis. Geostrophic velocities relative to 500 decibars (dbar) were calculated from station-to-station differences of dynamic height estimated using annual and semiannual harmonics. The geostrophic velocities calculated in the analysis were underestimated due to the large distance between stations (20 to 40 nautical miles) where the flow consisted of narrow currents such as the CU. As a result, Lynn and Simpson (1987) were unable to resolve much detail of the narrow CU and IC flows.

The results of the Lynn and Simpson (1987) analysis showed that the strongest equatorward flow of the CC occurred in spring and summer. The strongest flow of the poleward inshore countercurrent occurred in fall and winter. The dynamic height results at 200 dbar (with respect to the 500 dbar reference level) showed patterns of flow similar to that at the surface. Equatorward flow was weaker at this level, while poleward flow was broader and more coherent. Lynn and Simpson (1987) also utilized dynamic height results to define regions where the influence and phasing of the geostrophic dynamics differ markedly. This analysis readily identified the coastal, offshore, and transition zone discussed previously.

Several generalizations were made about the CC and IC based on geostrophic velocity. The CC was apparent as a 26.0 kg/m^3 isopycnal flow, with speeds exceeding 4 ecm/s not extending below 150 meters (m). The seasonal IC was very narrow; where it exceeded 4 cm/s velocity, it was observed only between the inshore stations along a given CalCOFI line.

Plots of surface flow by Lynn and Simpson (1987) show strong regional differences. The regions can be simplified as central California, southern California, and Baja California regions. The core of the surface equatorward flow off Central California was approximately 200–300 km offshore, with peak velocities occurring during the latter half of the year. Analysis of near surface characteristics, in particular, the mean distribution of salinity for July on a density surface of 1025 kg/m^3, showed a tongue of low salinity water being advected equatorward by the mean geostrophic flow roughly parallel to the coast line. This pattern occurred in other months of the year (Lynn, Bliss, and Elber 1982).

In the central California region, the lowest salinity was found near the surface. As it travels equatorward, the CC transports waters with salinities as low as 33.7 to the vicinity of CalCOFI line 130 off southern Baja. During the presence of a strong IC in January, waters with salinities greater than 33.8 were found beyond the continental slope.

In general, the low-salinity (and low-temperature) core existed in regions of stronger equatorward flow. The low salinity core was a good descriptor of the inshore path of the equatorward California current.

Analysis of the subsurface flow, the CU, at 250 meter depth, showed that it generally did not extend beyond 100 kilometers from the coast. There was a tendency for flow to be poleward year-round at certain depths in many locations. In areas that experienced a seasonal interruption of poleward flow, the interruption generally occurred over a period of two to three months in the spring.

C. THESIS GOAL

Subsequent to the analyses reported by Lynn and Simpson (1987), the CalCOFI observation grid shrank to include quarterly surveys of the Southern California bight. It is notable that the CalCOFI station grid has stations spaced 20 nautical miles to 40 nautical miles apart along onshore-offshore directed lines that are spaced 40 nautical miles. The NAVO surveys offered not only the opportunity to re-observe Central California waters, but also to resolve mesoscales (~10 nautical miles) and extend the depth of observations to 1000 m along CalCOFI lines.

The goal of this thesis is to provide a detailed analysis of the CCS structure near the surface as well as at intermediate depths. This will include a look at its mean structure over half a decade, as well as the temporal scale of individual research cruises (about two weeks). This thesis should also motivate further observational and modeling research to understand the structures of the California Current observed by the NAVO cruises.

II. DATA AND METHODS

The CTD and ADCP data analyzed in this thesis was collected off the Central Coast of California between 35°-38°N latitude and 122°-125°W longitude. Additional data used were satellite observations of sea surface height anomaly (SSHA) covering the temporal and spatial periods of the cruises. SSHA was obtained from the AVISO ocean observation website (http://www.aviso.oceanobs.com).

It was decided to analyze water properties and acceleration potentials on the shallow 26.0 kg/m^3 isopycnal and the intermediate depth 26.8 kg/m^3 isopycnal. This decision was made following a study of a temperature and salinity (T/S) properties of the combined survey data for all ten cruises (Figure 1). The 26.0 kg/m^3 isopycnal was chosen as it lies within the shallow halocline which is upwelled at the coast. The deeper 26.8 kg/m^3 isopycnal marked the lower part of the thermocline; from the observed T/S properties it exhibited variability over a large range of properties corresponding to influences of Equatorial and Subarctic Intermediate waters. Choosing isopycnals encompassing different T/S regimes allowed for analysis of how flow and water properties on the two density surfaces differed both spatially and temporally. It will also define the structure of the coastal and transition zones within the CCS.

To simplify the description of water masses, a state variable called spiciness (a concept first introduced by Stommel [1962] and called "spiciness" following Munk [1981]) was utilized. Distributions of potential temperature, θ, and salinity, S, are not independent, and a vertical profile of either contains information on the density stratification. For the CCS, spiciness, $\pi(\theta,S)$, defined by Flament (2002), is used extensively. Spiciness is most sensitive to isopycnal variations and is least correlated with the density field. Spiciness is largest for hot and salty water (spicy). Spiciness is ideal for delineating the boundary between water masses at shelf-slope and coastal upwelling fronts in the CCS (Flament, 2002)

The range of spiciness and associated water properties observed by the NAVO cruises for the 26.0 kg/m^3 and 26.8 kg/m^3 density surfaces is shown by the gray area in

Figure 1. Spiciness (potential temperature, salinity) ranged from -0.4 kg/m^3 (8.5°C, 33.45) to 0.4 kg/m^3 (11.3°C, 33.8) on the 26.0 kg/m^3 density surface. For the deeper 26.8 kg/m^3 density surface, spiciness (potential temperature, salinity) ranged from -0.35 kg/m^3 (5.5°C, 33.95) to 0.15 kg/m^3 (7.2°C, 34.25).

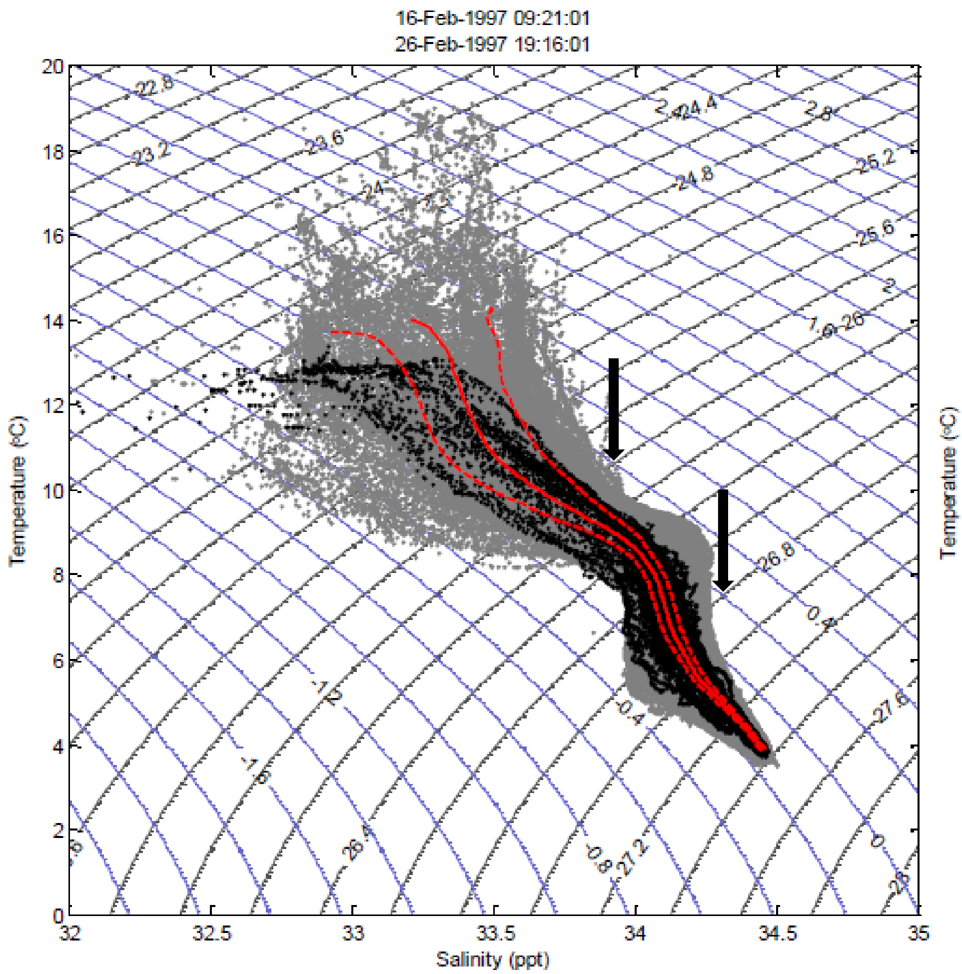


Figure 1. T/S Diagram for February 1997 cruise. Black dots are data from the February 1997 cruise, and grey dots represent data from all 10 NAVO cruises. The solid (dashed) red line is the mean (± one standard deviation) of salinity as a function of potential temperature for all 10 NAVO cruises. Density anomalies are shown on the curved lines that slope upward to the right and spiciness is shown by the curved lines that slope downward to the right. Black arrows designate 26.0 and 26.8 kg/m^3 density surfaces.

A. CRUISE DESIGN

The data for this thesis were collected over a five year period from 1997 to 2002, and the station pattern was based on the CalCOFI protocol (which was adopted for regional scientific surveys along the California coast in 1950) (http://www.calcofi.org). The sampling region consisted of a maximum of nine lines oriented perpendicular to the coast at 40 or 80 kilometer spacing, and included CalCOFI lines from 60 to 73.3. Spacing along lines was 18.5 km (10 nautical miles). CTD casts extended to 1000 dbar, or to near bottom for shallower depth regions.

The domain surveyed by the NAVOCEANO cruises is shown in Figure 2. It remained largely the same for the 10 cruises, but with some variations, so the resulting occupation frequency was different for different stations. To ensure the best coverage, a polygon (shown with a red line in Figure 2) was used for reconstruction of pressure, temperature, salinity, and spiciness fields for each cruise. The polygon has a length of approximately 222 km along the California Coast, and extended from 140 to 175 km offshore. The largest extension of the survey area was along CalCOFI line 67, starting at the shore of Monterey Bay. Following Lynn and Simpson (1987), the survey area addressed here included the inshore coastal region and part of the transition zone.

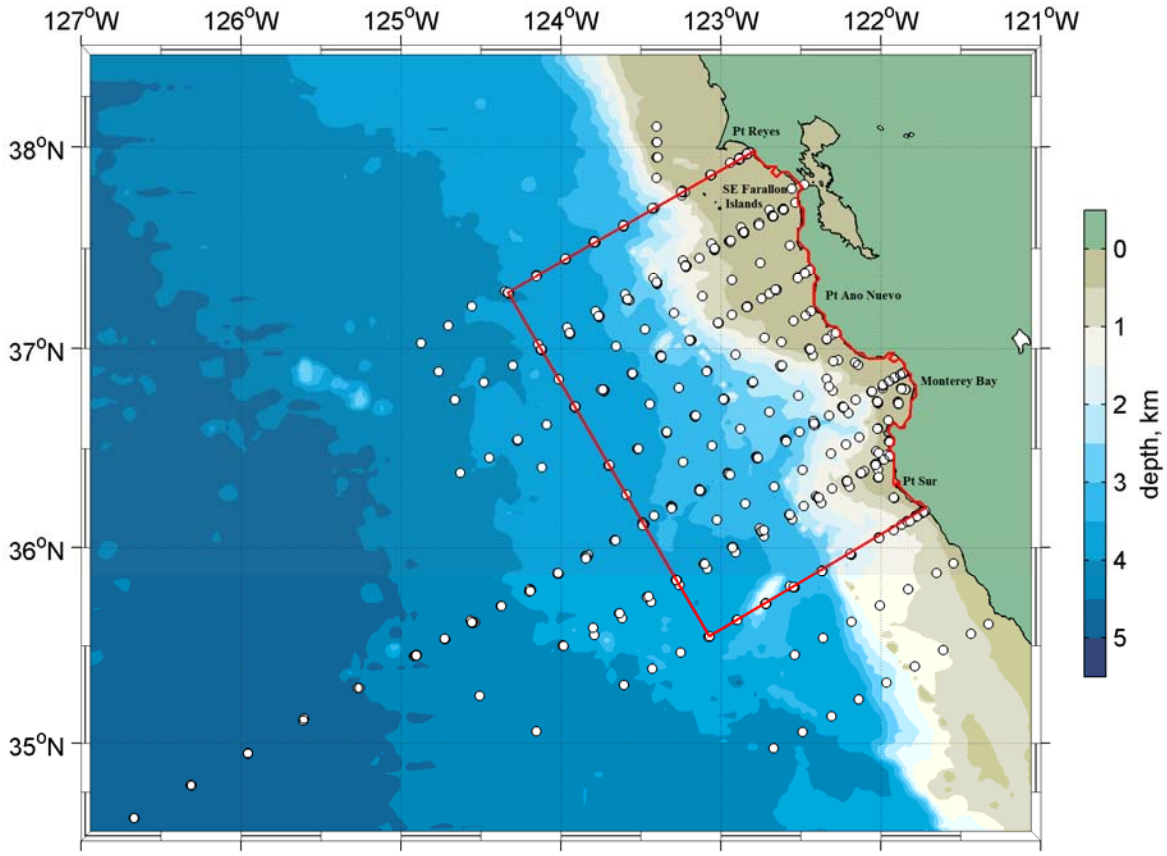


Figure 2. Stations occupied during ten Naval Oceanographic Office surveys of Central California coastal waters, 1997–2002. The area enclosed by the red line was used for optimum interpolation and calculation of mean fields.

B. CTD DATA AND ACCELERATION POTENTIAL

A SeaBird 911plus CTD was used to measure the conductivity, temperature, and pressure at each hydrographic station (with a 24-Hertz sampling rate). Where depth permitted, data was collected to 1000 m. The CTD data was processed using SeaBird software into a table of two dbar bins for each cast (JPOTS editorial panel, 1991). SeaBird and MATLAB software subsequently derived seawater quantities from these two dbar data including specific volume anomaly, density anomaly, and geopotential anomaly using the 1980 Equation of State (Fofonoff, 1985).

Acceleration potential, A, is calculated by integrating the density anomaly from the reference level. It was suggested as a method for representing flow in isentropic surfaces by Montgomery (1937) and is defined according to Montgomery and Stroup (1962) as $A = \phi_a + p\delta = p_0\delta_0 + \int_{\delta_0}^{\delta} p d\delta$, where $\phi_a = \int_{p}^{p_0} \delta dp$ is the geopotential, p_0 is the reference pressure, δ is the specific volume anomaly, and δ_0 is the specific volume anomaly at the reference pressure. After the acceleration potential is calculated, the geostrophic velocity can be calculated using $-2\Omega \sin\phi v = -\frac{1}{a\cos\phi}\frac{\delta A}{\delta\lambda}$ and $-2\Omega \sin\phi u = -\frac{1}{a\cos\phi}\frac{\delta A}{\delta\lambda}$, where a is the radius of the earth, ϕ is latitude, λ is longitude, and Ω is the rotation of the earth (Huang and Qiu, 1993).

Steric height for the sea surface (0/1000 dbar) was determined from $\int_{0}^{1000} \delta dp / g$, where g is determined from gravitational acceleration.

C. ADCP AND STREAM FUNCTION

VMADCP data were processed using CODAS (Common Ocean Data Access System) software developed by Eric Firing and Jules Hummon of the University of Hawaii (http://currents.soest.hawaii.edu/docs/adcp_doc/index.html). Currents in the upper ocean were measured with a 150 kHz narrow band VMADCP. Currents were resolved into eight meter bins from 15 to ~400 m when water depth and acoustic conditions permitted. Shipboard gyro heading used in VMADCP data collection were corrected using Ashtech GPS derived observation of ship's heading. Analysis of ADCP data was only conducted for the 26.0 kg/m3 isopycnal, as the VMADCP did not reach to depth and pressure levels at which the 26.8 kg/m3 isopycnal was present.

The velocity field obtained using the VMADCP can be used to determine the stream function of the field (Carter and Robinson, 1987). This approach used the divergence of stream function, $\nabla^2\psi = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$, where u(v) is the east-west (north-south) component of velocity and x(y) is east-west (north-south). This equation is solved using a standard Poisson solver with appropriate boundary conditions (shown in Figure 3), which are determined from the definition of the stream function, $\partial\psi / \partial x = v$, $\partial\psi / \partial y = -u$.

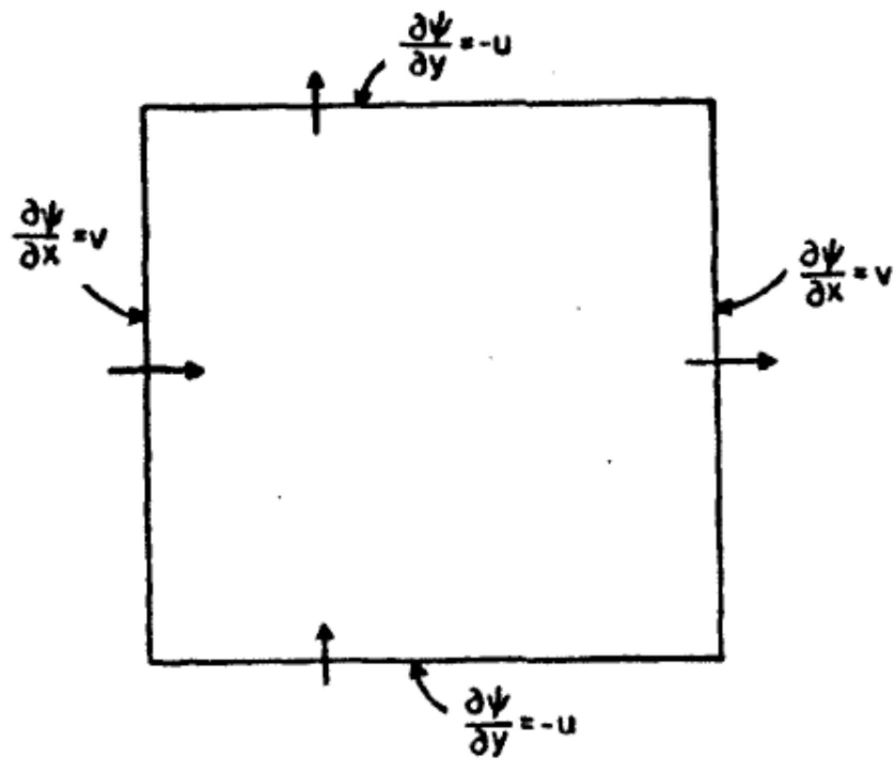


Figure 3. The boundary conditions (and the direction convention of the derivatives) for the calculation of the stream function from velocity. From Carter and Robinson (1987).

D. OPTIMAL INTERPOLATION

MATLAB® was used for data analysis. Optimal interpolation was utilized to map water properties onto density surfaces for each survey (Carter and Robinson 1987). Optimal interpolation deals with scalar, vector, and multivariate data sets, thus directly applicable to the data analyzed in this thesis. Optimal interpolation allows gappy data sets (as was the case in the NAVO surveys) to be mapped onto a standard grid (Carter and Robinson 1986).

In this thesis, three-dimensional fields have been reconstructed using CTD measurements interpolated every two 2 dbar, and the isotropic Gaussian covariance function for field fluctuations was used for each horizontal layer. The field fluctuations were calculated as differences between observations and a best-fit plane estimate. The correlation radius (length scale) of 50 km was used for both scalar and vector data. The same radius was applied to optimally interpolate ADCP data. In the latter case, the covariance matrix was estimated from the data as described in Carter and Robinson (1987). From the reconstructed 3-D fields, depth (pressure) of the shallow and intermediate isopycnals has been calculated, and all water properties were then mapped on these respective surfaces.

THIS PAGE INTENTIONALLY LEFT BLANK

III. STATISTICAL ANALYSIS

The first result of this study is a description of the mean fields and their standard deviation for each density surface. Properties that will be described are pressure, spiciness, and acceleration potential. For the 26.0 kg/m^3 surface, stream functions produced from ADCP data will also be presented. Note that values are shown only for locations where the density surface was observed on each of the ten surveys.

A. PRESSURE

The mean pressure on the 26.0 kg/m^3 isopycnal and on the 26.8 kg/m^3 isopycnal is shown in Figure 4. On the 26.0 kg/m3 isopycnal (Figure 4, upper), pressure was lowest near the coast and increased with increasing distance offshore. The minimum pressure near the coast ranged between 85 and 90 dbar in three separate shallow areas. Along the western boundary, the 26.0 kg/m^3 surface was deepest off Pt. Sur, ~120 dbar, shoaled to 100 dbar, and then deepened to a pressure of 110 dbar at 37°N.

Contrasting with the topography of the shallow halocline density surface, the 26.8 kg/m^3 isopycnal (intermediate water surface) shoaled to the west (Figure 4, lower). Although the region in Figure 4 only extended 175 km from the coast, maximum pressure is seen to the east of the offshore edge of the chart, clearly defining a pressure ridge. The pressure ridge, as defined by the area shallower than 375 dbar was broader in the central and northern portions of the survey region but narrowed to the south of Pt. Sur.

Standard deviations of pressure on the shallow and 26.8 kg/m3 isopycnals are shown in Figure 5. On the 26.0 kg/m3 isopycnal there was a large deviation near the coast between 37°N and 37.5°N, and on the western edge between 36°N and 36.5°N (26–30 dbar) (Figure 5, upper). On the 26.8 kg/m3 isopycnal, there is an isolated area of high standard deviation (upwards of 35 dbar); while elsewhere deviation from the mean is mostly less than 25 dbar (Figure 5, lower).

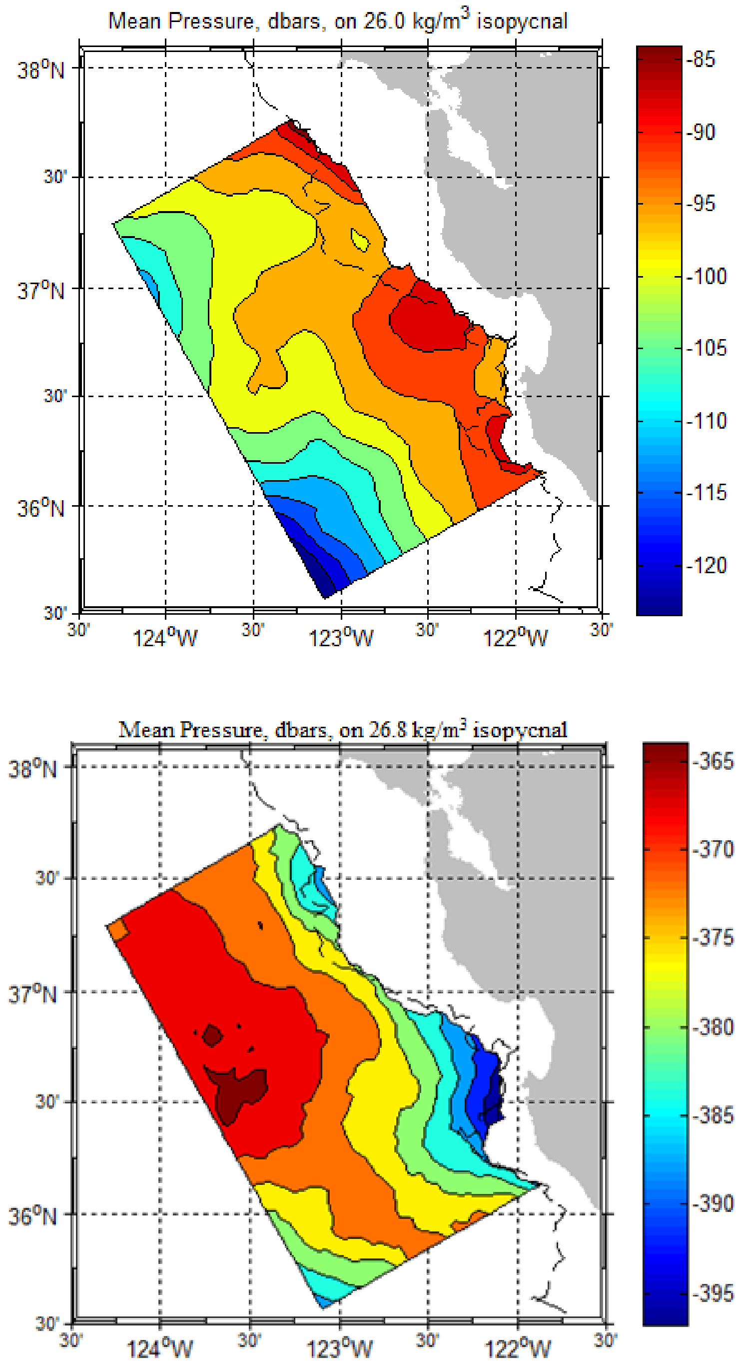


Figure 4. Mean pressure in dbar for the 26.0 kg/m^3 (upper) and 26.8 kg/m^3 density surfaces (lower). Contour interval is four dbar.

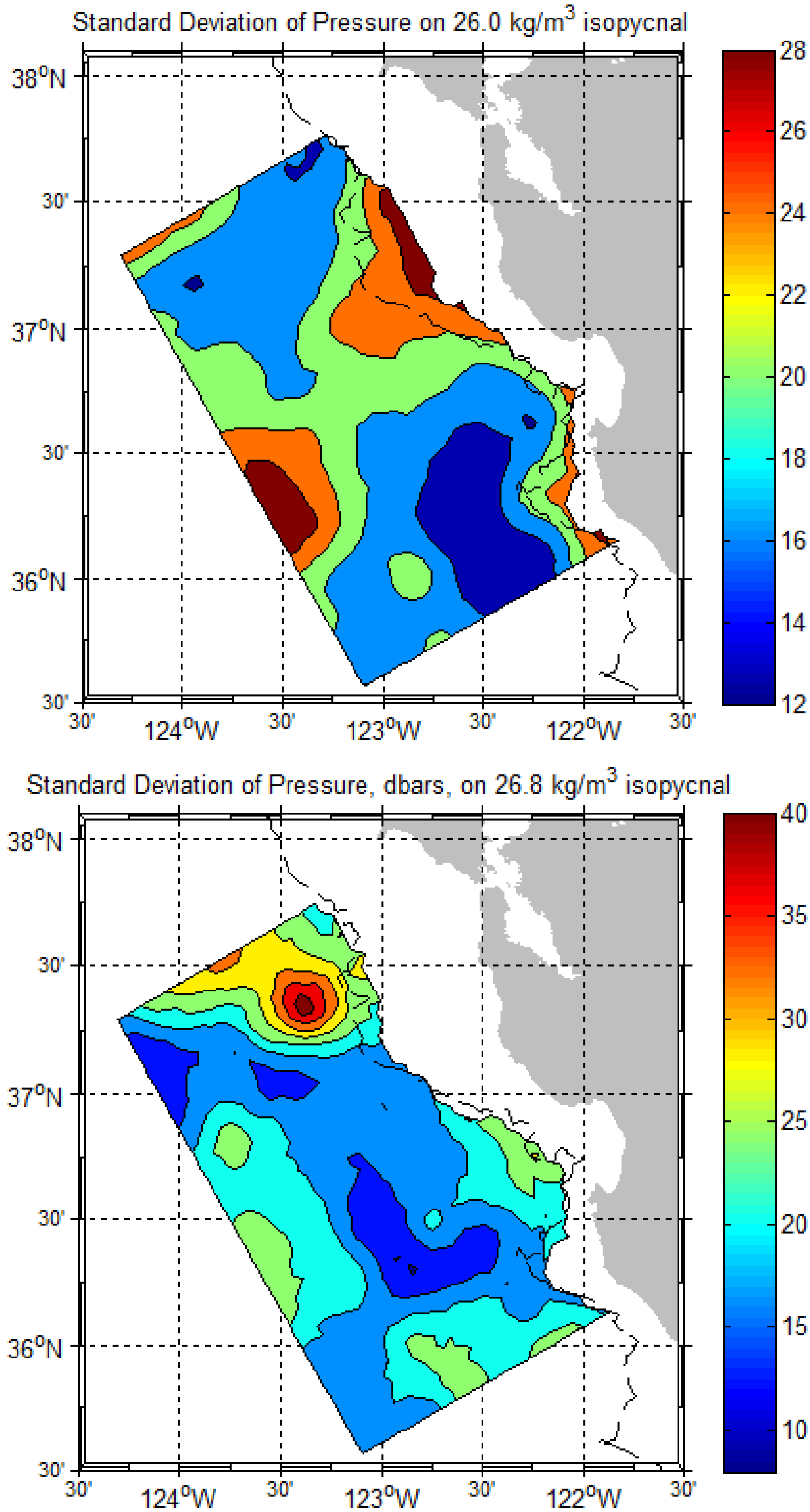


Figure 5. Standard Deviation of mean pressure in dbar for the 26.0 kg/m^3 (upper) and 26.8 kg/m^3 density surfaces (lower). Contour interval is four dbar.

B. SPICINESS

Mean spiciness is shown in Figure 6. As a consequence of upwelled and equatorial waters next to coast and subarctic waters offshore, both density surfaces exhibited lower spiciness levels along the offshore edge of the survey, which generally increased toward shore. The 26.0 kg/m3 isopycnal showed nine eddy-like features with closed contours and diameter ~40 km, but the 123°W meridian generally delineated higher spiciness inshore waters from lower spiciness to the west. On the 26.0 kg/m3 isopycnal, largest concentrations of spiciness were found next to the coast in two regions, one from Monterey Bay to Point Sur and the other from Point Año Nuevo to SW Farallon Island.

For the 26.8 kg/m3 isopycnal, the 123°W meridian also marked a gradient between higher spiciness inshore waters and lower spiciness offshore. A 50 km region immediately offshore of Monterey Bay was marked by high spiciness, greater than 16 kg/m^3 with tongues of greater than 0.1 kg/m^3 spiciness extending north and south along the continental margin. Lowest spiciness, less than -0.1 kg/m^3, extended over a region of about 100 kilometer diameter along 123.6°W.

The standard deviations for spiciness on both surfaces are shown in Figure 7. A larger standard deviation was seen on the 26.0 kg/m3 isopycnal, with narrow regions of standard deviation approaching 0.14 kg/m^3 on the eastern side near the coast. Elsewhere most standard deviations were less than 0.06 kg/m^3, with variability in the region to the southwest increasing to up to 0.10 kg/m^3. Standard deviation on the 26.8 kg/m3 isopycnal was less, with isolated maximums of 0.05 kg/m^3. The spatial variability of the standard deviations of spiciness for both surfaces was further evidence of eddy-like disturbances.

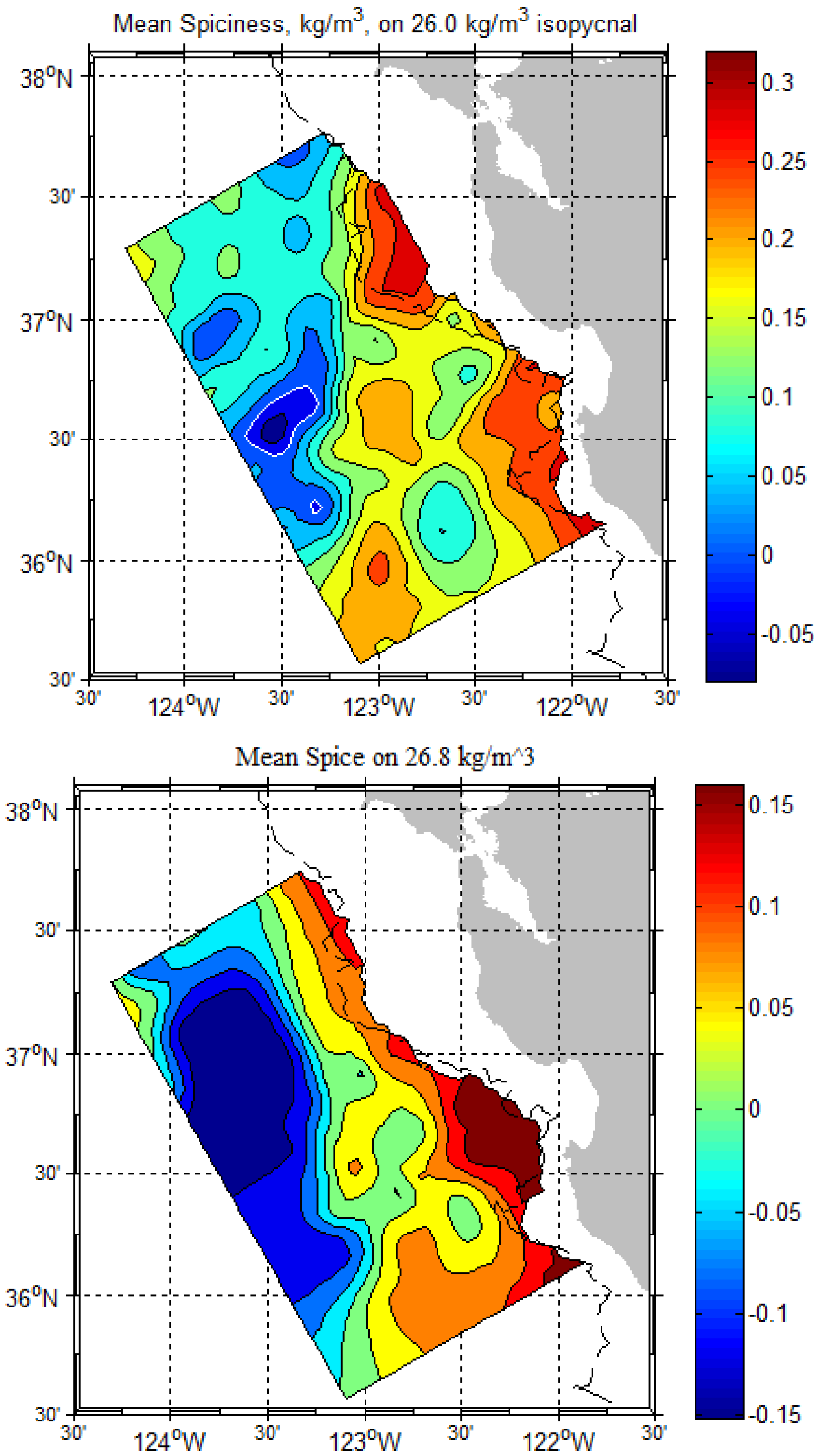


Figure 6. Mean spiciness in kg/m^3 for the 26.0 kg/m^3 (upper) and 26.8 kg/m^3 density surfaces (lower). Contour interval is .04 kg/m^3.

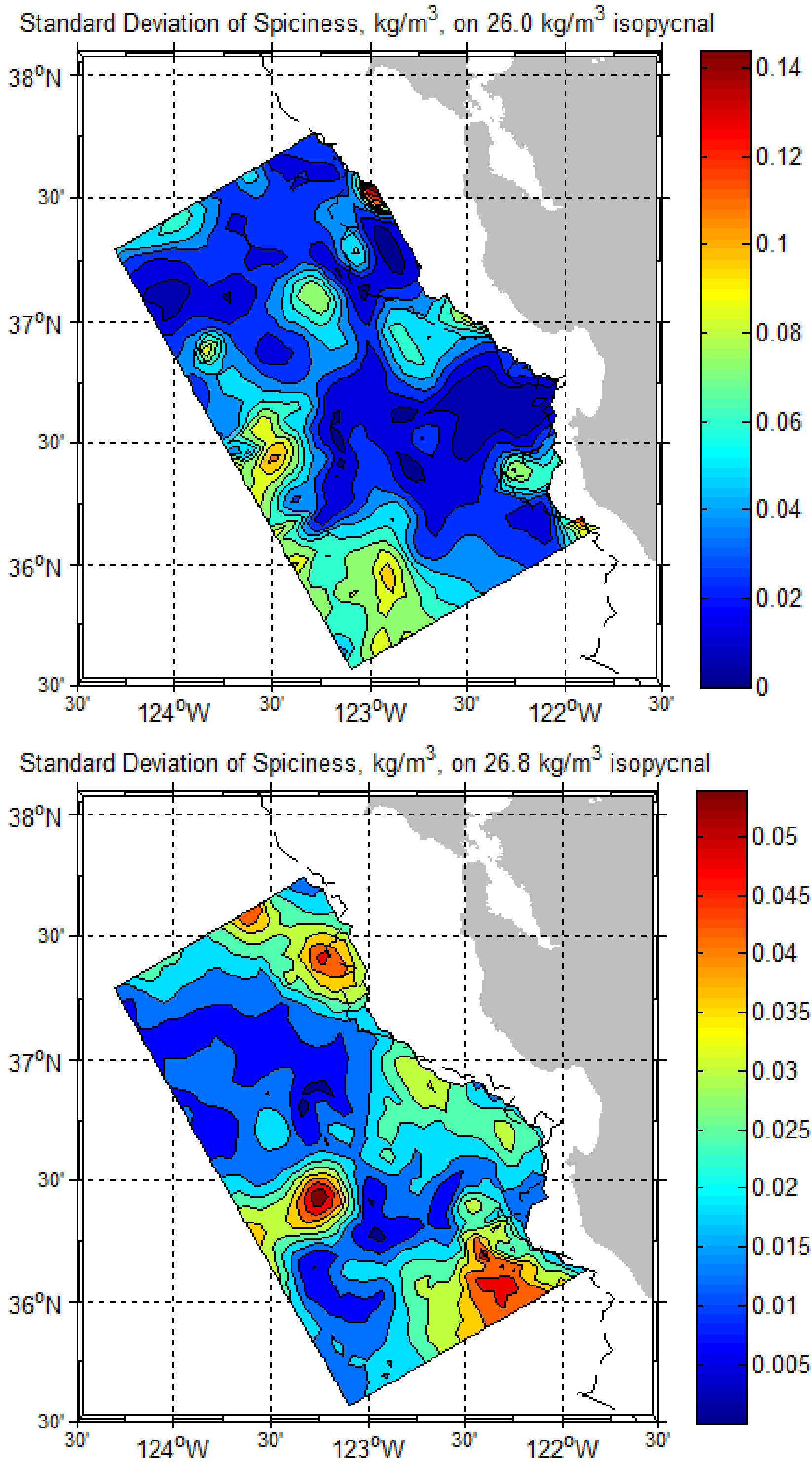


Figure 7. Standard deviation of mean spiciness in kg/m^3 for the 26.0 kg/m^3 (upper) and 26.8 kg/m^3 density surfaces (lower). Contour interval is .012 kg/m^3 (upper) and .005 kg/m^3 (lower).

C. ACCELERATION POTENTIAL AND STREAM FUNCTION

Acceleration potential and the stream function were used to analyze flow patterns. This allowed comparison of a geostrophic flow patterns (assuming zero-flow at 1000 dbar) to actual measurements (stream function derived from ADCP data). For the 26.0 kg/m3 isopycnal (Figure 8, upper), large acceleration potentials (12.55–12.60 J/kg) immediately to the south of Monterey Bay and offshore at the southwestern corner of the survey were linked by a ridge of 12.5 J/kg acceleration potential, indicating onshore flow to the north of the ridge and offshore flow to the south. A broad area of minimum geopotential, 12.35 J/kg, occurred 100 km to the west of Monterey Bay and corresponded to a pattern of cyclonic flow in the northern portion of the survey area. Poleward flow occurred at the eastern boundary. A region of maximum equatorward (CC) flow was seen on the southern boundary at longitude 122°40’W.

The stream function field (units 10 m^2/s), shown in Figure 8 (lower), are similar in appearance to the acceleration potential field. One difference was that the stream function showed more continuity of alongshore flow of the CU to the north of Pt. Sur. This was in part due to the fact that the stream function charts extended into water depths less than 1000 m. A second difference was that the offshore region of high stream function was much reduced.

Standard deviations for acceleration potential (Figure 9, upper) and the stream function (Figure 9, lower) showed lower deviations closer to shore for both (for stream functions this was affected by the fact that the velocity field is integrated from the coast). The standard deviation for acceleration potential was less than 0.3 J/kg for most of the region. An exception to this was in the west between 36.0°N and 36°30′N where the maximum deviation was greater than 0.40 J/kg along the western boundary. The increase in standard deviation moving away from the coast in the stream function figure was generally consistent throughout the survey area, reaching a maximum of 700 $10m^2/s$. in the same region where the maximum occurred on the acceleration potential figure (Figure 9, upper). An exception to the decreasing gradient was along the 37°N latitude as standard deviation of less than 400 $10m^2/s$ extended off the coast to a longitude of

123°30′W. Variability (standard deviation) increased with distance from shore; the larger variability was characteristic of the transition zone (Lynn and Simpson 1987).

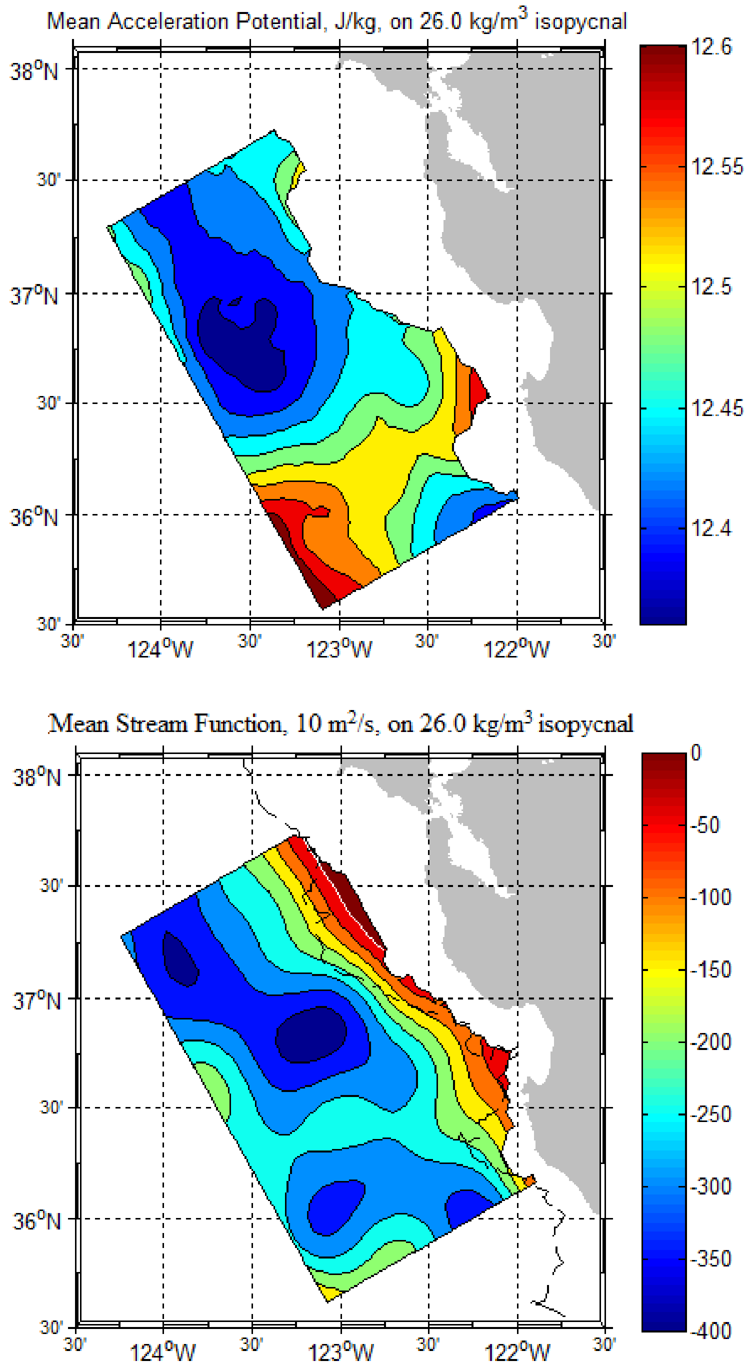


Figure 8. Mean acceleration potential in J/kg for the 26.0 kg/m^3 density surface (upper) and mean stream function in 10 m^2/s for the 26.0 kg/m^3 density surface (lower). Contour interval is 0.3 J/kg (upper) and 50 m^2/s (lower).

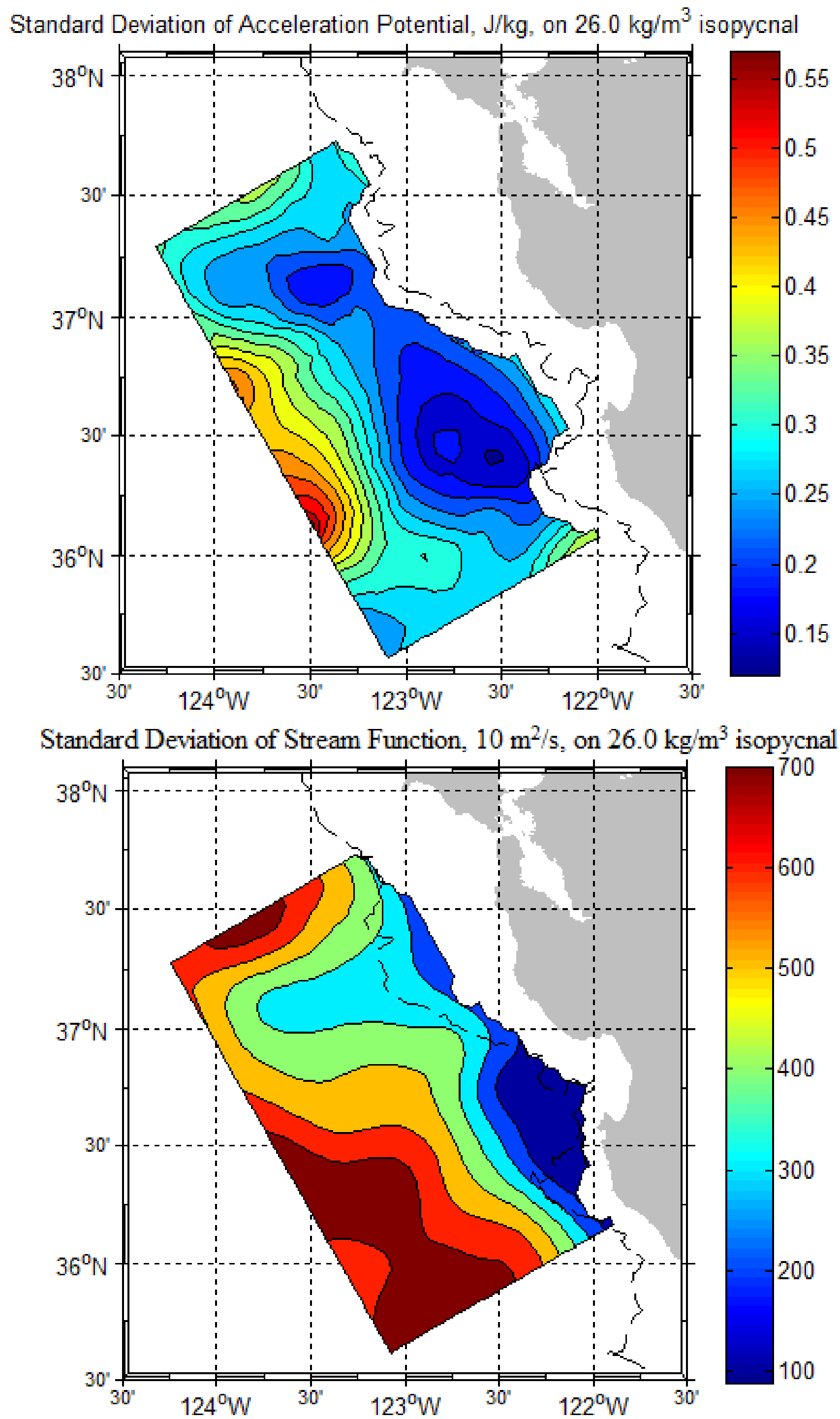


Figure 9. Standard deviation of mean acceleration potential in J/kg for the 26.0 kg/m^3 density surface (upper) and standard deviation of mean stream function in 10 m^2/s for the 26.0 kg/m^3 density surface (lower). Contour interval is .03 J/kg (upper) and 50 m^2/s (lower).

The pattern of acceleration potential on the 26.8 kg/m^3 isopycnal was similar to that on the 26.0 kg/m^3 isopycnal (Figure 10, upper). The maximum occurred offshore Monterey Bay (12.0–12.2 J/kg) but, at all latitudes was greatest at the coast. The strong gradient of the acceleration potential corresponded to poleward flow of the CU. Between the regions of minimum acceleration potential in the west (10.8–11.0 J/kg) there was a region of slightly larger acceleration near 36°30´N. It is possible that this elevated acceleration potential allowed for the transport of water from the transition into the coastal zone. Further evidence of this was shown in Figure 4, on the southern side of the summit of the ridge on the 26.8 kg/m^3 isopycnal near 36°30´N, 123°00´W.

The standard deviation of acceleration potential on the 26.8 kg/m^3 isopycnal is shown in Figure 11. A ~50 km wide region of low variability, <0.08 J/kg, extended northward along 123°W, followed the slope to the northwest, and then extended offshore along 37°N. Regions of larger variability, areas above 0.12 J/kg, were visible in the west, north, and east.

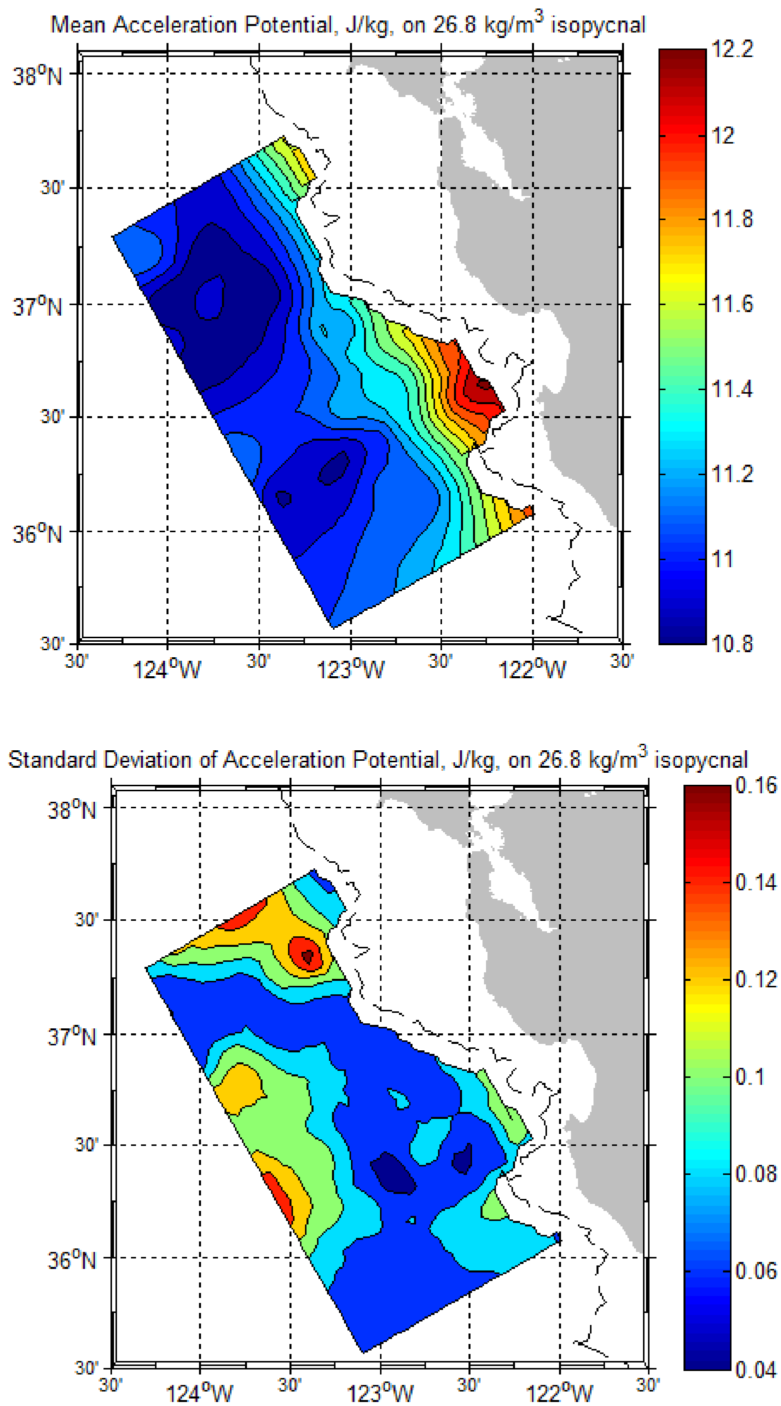


Figure 10. Mean acceleration potential in J/kg for the 26.8 kg/m^3 density surface (upper) and standard deviation of mean acceleration potential in J/kg for the 26.0 kg/m^3 density surface (lower). Contour interval is .02 J/kg (upper) and .01 J/kg (lower).

As discussed, the direct measurement of current using the ADCP allowed for comparison to using a geostrophic approximation to depict theoretical approach of producing a field of acceleration potential. The mean ADCP velocities on the 26.0 kg/m3 isopycnal, shown in figure 11 (and by the mean stream function in Figure 8, lower) were in general agreement with acceleration potential. A strong poleward flow is visible inshore, with eddy activity evident further offshore, transitioning to the appearance of equatorward flow on the western edge of the survey area. Two distinct cyclonic eddies occurred, one was centered at 36.75°N, 123°W offshore Point Año Nuevo and the second at 36°N, 123°W offshore Point Sur. This mean ADCP picture over five years of survey data gives the appearance of IC/CU inshore, moving offshore through a transition zone of eddy activity, to where inshore and offshore waters are exchanged, with vestiges of the core CC on the western edge of the survey range..

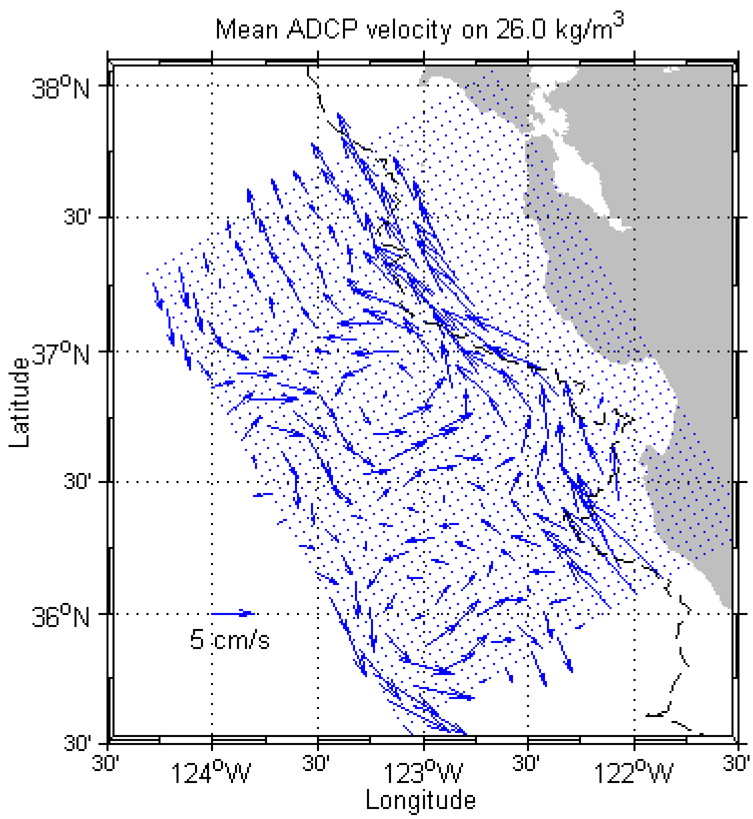


Figure 11. Mean ADCP velocity on 26.0 kg/m^3 isopycnal.

D. SEA SURFACE HEIGHT AND STERIC SEA LEVEL (0/1000 DBAR)

In addition to utilizing NAVO data, satellite altimeter was utilized to analyze changes in sea surface height anomaly (SSHA) during the cruise period. Altimeter products were produced by *Ssalto/Duacs* and distributed by *Aviso,* with support from *CNES* (http://www.aviso.oceanobs.com/duacs/). Latitude and longitude boundaries were chosen so as to ensure that the survey area was encompassed with the downloaded data, whereupon fields of SSHA were produced (Figure 12). Note that the accuracy of altimetry data can decrease in coastal areas. Several reasons influence this. First, there is an increased uncertainty of corrections applied to the data, e.g., tidal corrections, land effects. This makes the data within 25–50 km off the coast less reliable. Second, the data used here is interpolated both in space and time, and may not be satisfactory to resolve rich mesoscale features, which are characteristic for the coastal regions. Also, the effect of the side lobes of satellite altimeter reflecting off of land can have an adverse effect.

The ten NAVO surveys covered less than 20 weeks for the five-year period 1997–2002. To see how representative the statistics presented above might be, continuous measurements of sea surface height anomalies (SSHA) from satellite altimeter data were examined. The mean values from the entire data set were compared with the mean value of a subset of SSHA charts for the dates of the NAVO cruises. The mean steric height for all cruises (geopotential) was also computed, (from zero to 1000 dbar).

Continuous daily data from February 1997 to November 2002 were obtained (Figure 12, upper), along with daily data from the central cruise day for each of the 10 cruises (Figure 12, center). Mean SSHA for the ten NAVO cruises proved similar to that of the continuous time mean. Both data sets showed a near-zero anomaly towards the central part of the survey area, with an increasing anomaly gradient to the north and the south. Moving towards the western edge of the survey area, there was a negative anomaly gradient for both data sets. The appearance of the negative gradient from the northeast part to western edge should give rise to geostrophic flow to the right, which corresponds with the CC on the western fringe of the survey area. A negative gradient was also visible directed in a northeasterly direction (from 36.00°N, 123.00°W to 36.50°N, 122.25°W, evidence of resulting geostrophic flow in a poleward direction inshore.

In the fields of standard deviation of SSHA , the magnitudes of standard deviation were similar, though the overall pattern differs somewhat. Standard deviation of the continuous data has three regions of maximum deviation, with minimums visible to the northwest and southeast (Figure 13, upper). The NAVO results resemble the pattern described by Lynn and Simpson, with low variability near the coast and offshore but high variability in the middle transition zone (Figure 13, center).

The mean steric height (geopotential) for all cruises is shown in Figure 12 (lower). The geopotential was computed from zero to 1000 dbar. The contours of geopotential are called isosteres and are streamlines for geostrophic flow. The strength of the geostrophic flow is inversely proportional to the distance between isosteres and the direction of flow is along the isostere so that values of larger geopotential are to the right of the direction of flow. From this was it evident that strong mean flow occurred in the southern part of the survey area, and skirted along the western edge, with flow directed towards the equator (as the values of geopotential in this region increase with distance from shore). In the northeast part of the survey area between 37.0°N and 37.5°N there was small region of poleward flow near to the shore as geopotential increases from 12.9 J/kg to 13.1 J/kg.

The standard deviation of steric height (geopotential), shown in Figure 13 (lower), was largest in the regions of strong flow, as it was generally larger than 0.45 J/kg in the south and along the western edge of the survey region. The least variability occurred just off of the Monterey Bay where standard deviation was ~0.35 J/kg.

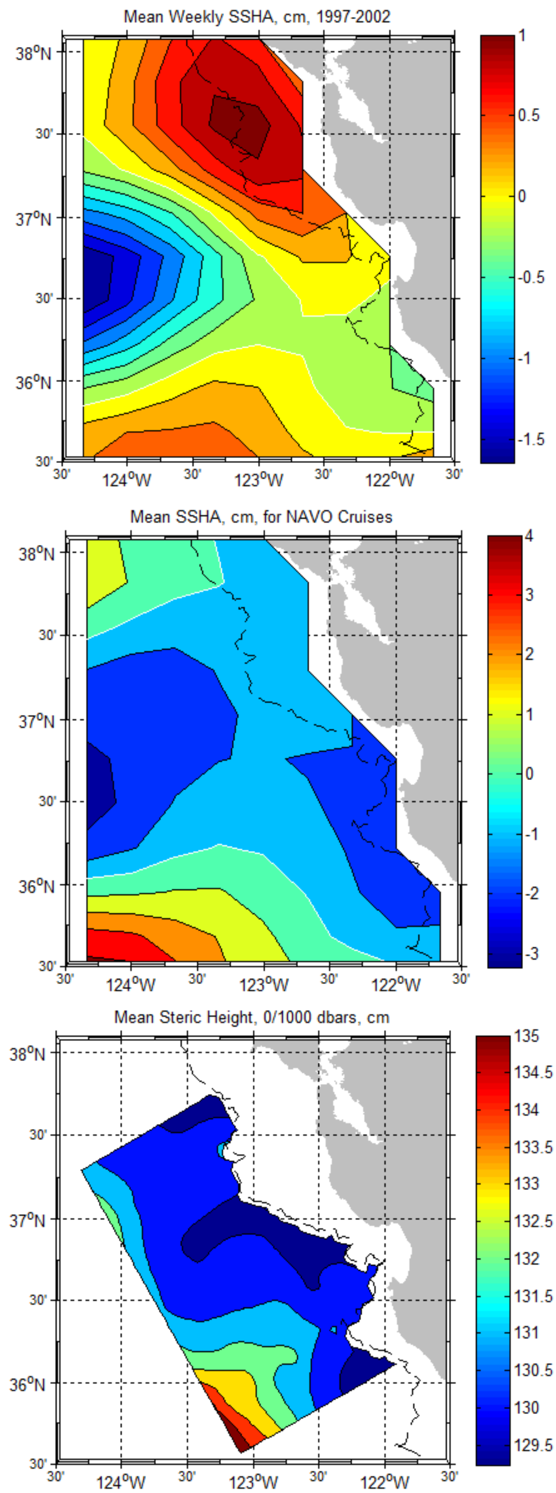


Figure 12. Mean SSHA. Daily Data Feb 1997–Nov 2002, contour interval 0.2 cm (upper), mean of central NAVO cruise days, contour interval 0.2 cm (middle), and mean steric height from 0–1000 dbar, contour interval is 1cm

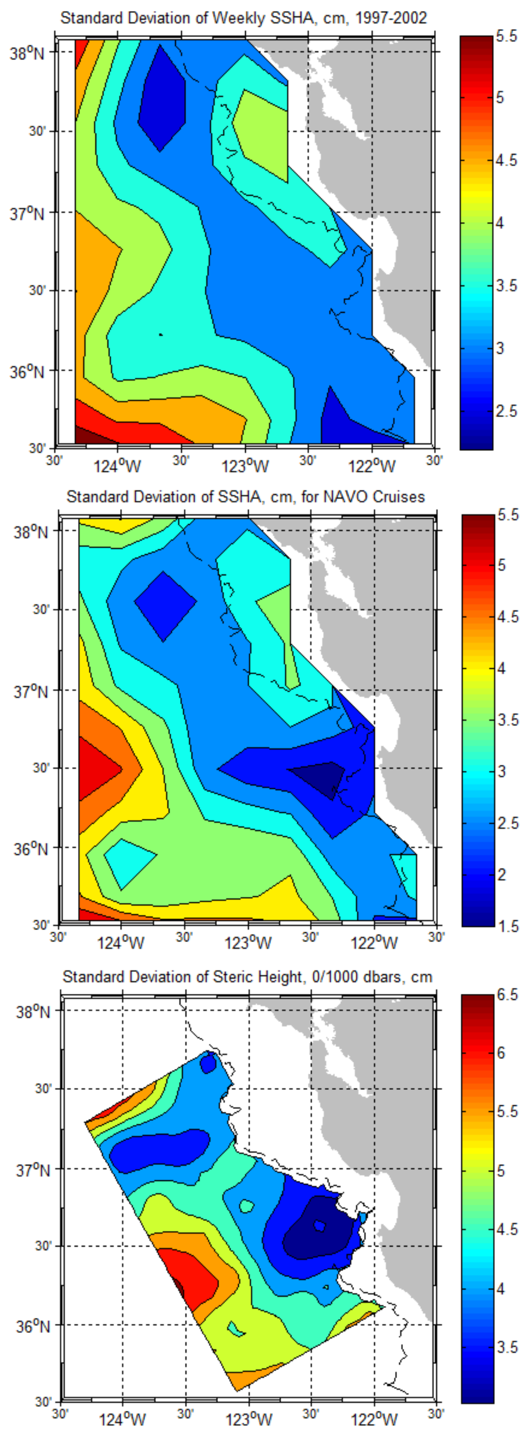


Figure 13. Mean SSHA standard deviation. Daily data Feb 1997–Nov 2002, contour interval 0.5 cm (upper). Mean of central NAVO cruise days, contour interval 0.5 cm (center). Steric height standard deviation, contour interval is 0.05 cm (lower)

E. SUMMARY

This chapter described the mean fields and their standard deviation for each density surface. On the 26.0 kg/m^3 surface the pressure field was shallowest near the coast and increased with distance offshore. The 26.8 kg/m^3 surface contrasted this by shoaling to the west and showed evidence of a broad pressure ridge through the survey area. Pressure standard deviations on the 26.0 kg/m3 isopycnal were largest in areas of shallow pressure levels and on the western edge where the central pressure ridge persisted. The largest variation on the 26.8 kg/m3 isopycnal occurred in a region of decreasing pressure gradient moving towards shore in the northeast part of the survey area.

Mean spiciness levels were lower along the offshore edge of the survey for both density surfaces, a result of upwelled and equatorial waters next to the coast and subarctic waters offshore. The 123° meridian generally delineated a separation between these water masses on both surfaces. Maximum standard deviation of spiciness was 0.14 kg/m^3 on the 26.0 kg/m3 isopycnal and 0.05 kg/m^3 on the 26.8 kg/m3 isopycnal. The overall spatial variability of spiciness is evidence of eddy-like disturbances within the survey area.

The mean acceleration potential and stream function statistics allowed for comparison of a model to actual measurements (on the 26.0 kg/m^3 surface). The stream function (derived from ADCP data) was similar in appearance to acceleration potential; poleward alongshore flow was visible inshore (flow for which the stream function showed more continuity), cyclonic recirculation to the north of Monterey Bay, and offshore flow to the south of Pt. Sur. The acceleration potential field on the 26.8 kg/m3 isopycnal showed similar poleward flow. The standard deviations of these fields showed a general increase in variability moving away (an exception being low variability along 123° west on 26.8 kg/m3 isopycnal), indicating the presence of a coastal transition zone. The plot of five-year mean ADCP velocity in Figure 11 gave further evidence of the IC/CU inshore, and transition zone with vestiges of the CC on the western boundary.

Comparison of Mean SSHA for the ten NAVO cruises was similar to the continuous time mean data. The anomaly gradients for both generally correspond to the expected IC/CU, transition zone, and parts of the CC along the western boundary. The standard deviation fields were overall similar with minor differences in locations of maximum and minimum variability. The strongest feature visible for the mean geopotential field was equatorward flow in in the southern and western edge of the survey area, with variability highest in the regions of strong flow (i.e., closely spaced contours of geopotential).

IV. INDIVIDUAL CRUISE ANALYSIS

Chapter III provided an analysis of the statistical means and standard deviation of survey and AVISO data to produce a general description of the combined results of all cruises, spread over the temporal scale of five years. In this chapter, results from the individual cruises will be described.

A. FEBRUARY 1997

The February 1997 survey was done by *R/V Point Sur,* which departed Moss Landing at 1648Z on 11 February. CTD observations began on 0200Z, 13 February, and a chart of CTD station positions is shown in Figure 16. Two 25-hour time series with CTD casts every two hours were done on the continental shelf in the Gulf of the Farallones: at 37°-56.5´N, 122°-53.4´W, in water 45 m deep beginning at 0330 on 13 February, and at 37°-32.2´N, 122°-45.6´W in water 45 m deep at 0720Z on 14 February. The cruise was interrupted by two engine failures, 1500–2000Z, 12 February in San Francisco, and 2200Z, 17 February, 2200Z, 20 February, in Alameda. The cruise was completed on 2310Z, 25 February, in Moss Landing.

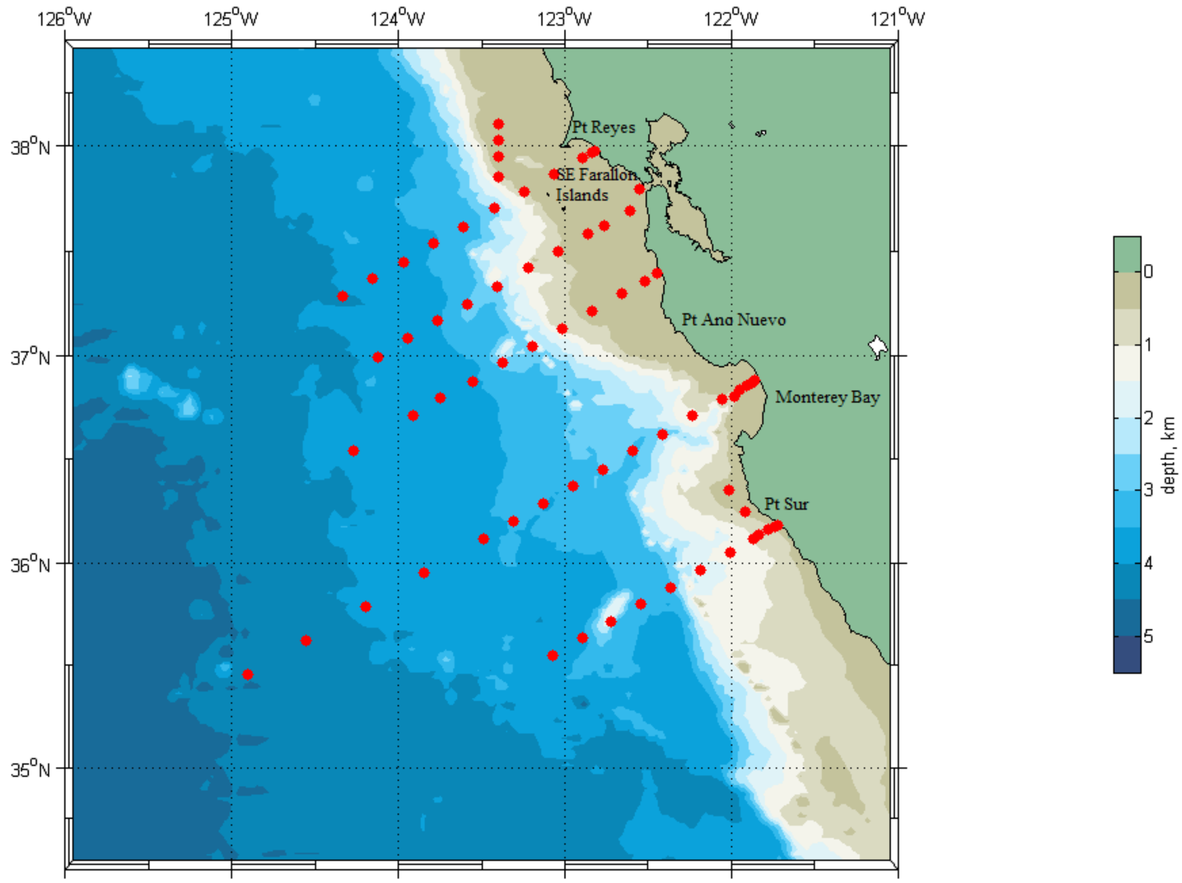


Figure 14. Station positions for February 1997 (shown by red dots).

1. T/S Diagram

The range of water properties observed for the February 1997 cruise is shown by the black dots in Figure 1. Surface water temperatures were less than 13°C with salinity 33–33.5. Spiciness (potential temperature, salinity) ranged from approximately -0.15 kg/m^3 (9.1°C, 33.55) to 0.2 kg/m^3 (10.1°C, 33.80) on the 26.0 kg/m^3 density surface. For the deeper 26.8 kg/m^3 density surface, spiciness (potential temperature, salinity) ranged from approximately -0.25 kg/m^3 (5.9°C, 34.00) to 0.05 kg/m^3 (7.1°C, 34.20).

2. Pressure

Figure 15 displays the pressure fields for February 1997. Along the 26.0 kg/m^3 isopycnal surface, a minimum pressure of 13.2 dbar occurred in the southeast portion of the survey area near to the coast (Figure 15, upper). North of 36°30′N, a trough was observed immediately to the west of the shelf with a maximum in pressure, 129–135 dbar, near, 37°05′N, 123°07′W. There was a ridge of lower pressure west of this maximum (86–98 dbar), and a deepening along the western edge, where pressure increased to 105–111 dbar in places along the western edge

On the 26.8 kg/m^3 isopycnal, the pressure maxima was observed to be 401–407 dbar, near 37°10′N, 123°00′W at the same location as for the 26.0 kg/m3 isopycnal (Figure 15, lower). From the maximum, pressure decreased to the south and west where the minimum pressure, 334 dbar, delineated the shallowest part of the pressure ridge at 36°45′N, 123°45′W and 36°15′N, 123°15′W. The offshore ridge visible at 362–369 dbar, extended from the northern part of the survey area south to 36°30′N, and thence eastward, bifurcating northward and southward next to the continental slope off Pt. Sur.

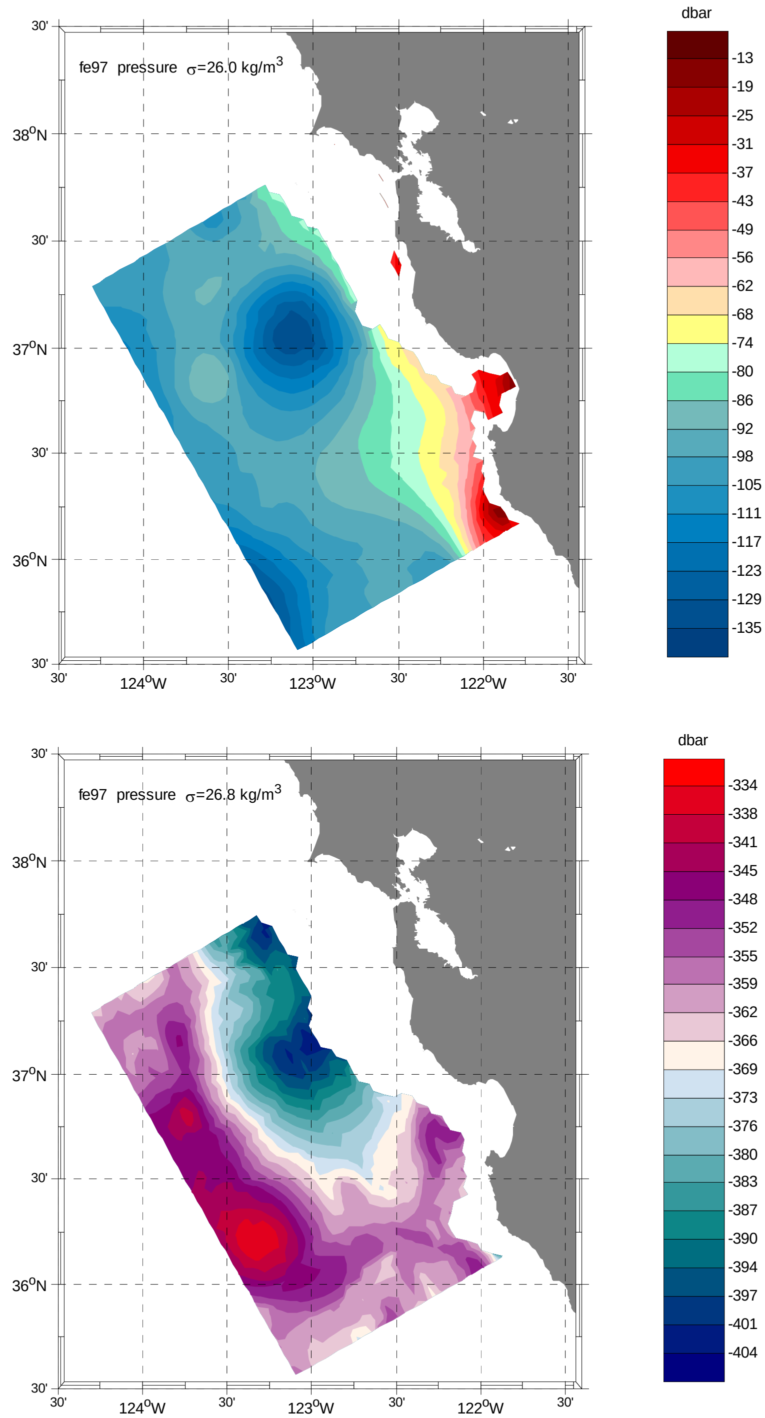


Figure 15. Pressure, dbar during February 1997 for the 26.0 kg/m^3 (upper) and 26.8 kg/m^3 density surfaces (lower). Contour interval is 6.1 dbar (upper) and 3.5 dbar (lower).

3. Spiciness

Figure 16 displays the spiciness field for February 1997. Along the 26.0 kg/m^3 isopycnal (Figure 16, upper), the maximum was observed in the southeast close to the coast, between Point Sur and Monterey Bay ranging between 0.44 kg/m^3 and 0.78 kg/m^3 (note that these high values of spiciness were observed by objective analysis and are not seen in the data shown in Figure 1). A region of spiciness less than zero was seen in the western part of the survey area between 36°37´N. The 0.2 kg/m^3 spiciness contour was oriented along 123°12´W delineating low spiciness offshore waters, but another band of low spiciness (0.2 kg/m^3) occurred inshore along 122°36´W.

A region of maximum spiciness, 0.25 kg/m^3, was also seen on the 26.8 kg/m^3 isopycnal immediately offshore southern Monterey Bay. The region of minimum spiciness was generally seen in the western portion of the survey area, with a minimum of approximately -0.15 kg/m^3 in the vicinity of 36°57´N, 123°30´W. The zero spiciness contour followed from meridians between longitudes 123°00´W and 123°30´W from south to north, delineating the offshore region of high spiciness from lower values of spiciness found inshore.

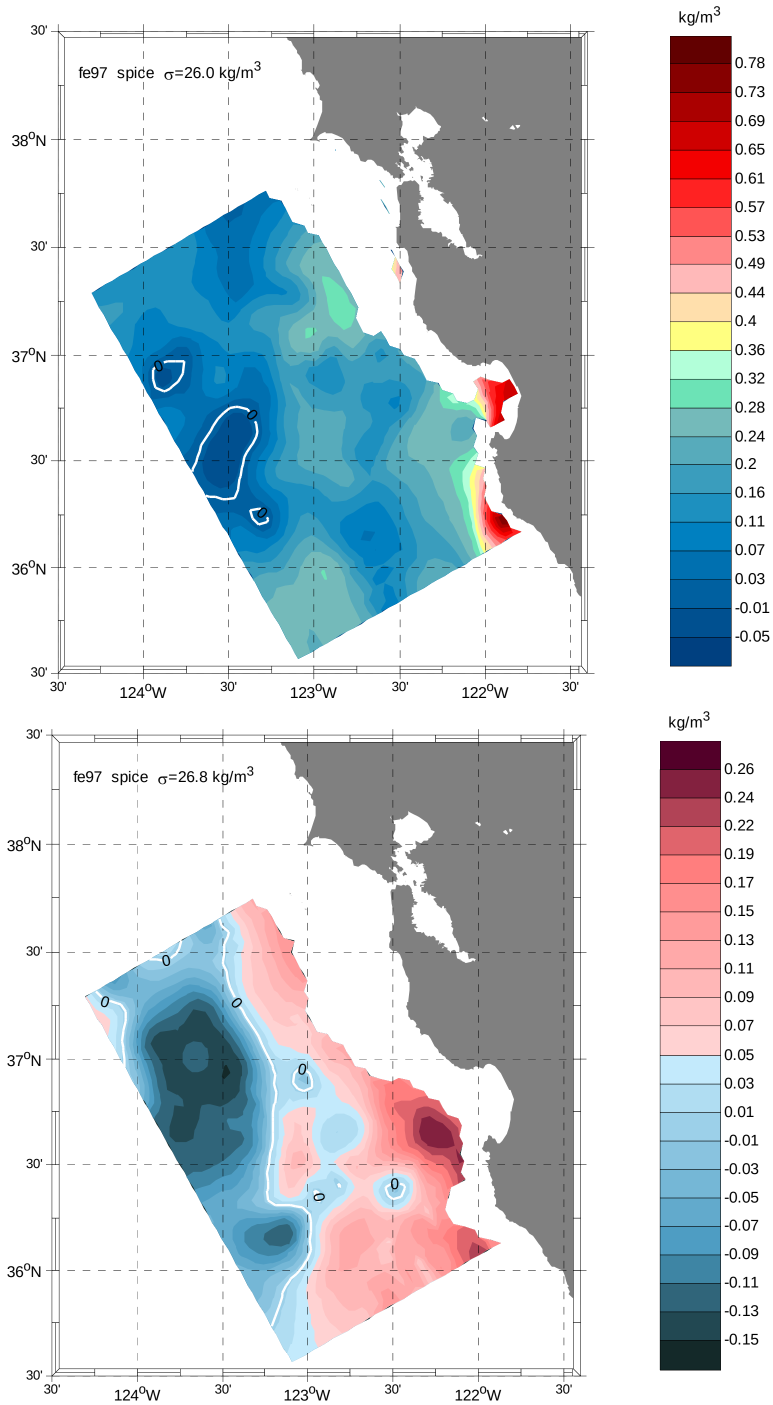


Figure 16. Spiciness in kg/m^3 during February 1997 for the 26.0 kg/m^3 (upper) and 26.8 kg/m^3 (lower) density surfaces. Contour interval is 0.041 kg/m^3 (upper) and 0.021 kg/m^3 (lower). White denotes zero spiciness contour.

4. Acceleration Potential and ADCP

Figure 17 (upper) shows acceleration potential on the 26.0 kg/m^3 isopycnal. There was a cyclonic flow on the western side of the survey area centered at 36°15′N, 123°17′W. Poleward flow was evident east of this cyclonic flow through the center of the survey. To the north, anticyclonic flow was centered at 37°05′N, 123°07′W.

ADCP data for the 26.0 kg/m^3 isopycnal are shown in Figure 17 (lower). The patterns of ADCP flow were distinctly different than those derived from acceleration potential, e.g., strong equatorward flow across the entrance of Monterey Bay. Poleward flow over the continental margin occurred in the northeast and southeast parts of the survey area. Flow features are similar in appearance to those seen on Figure 16 included strong cyclonic flow centered around 36°13′N, 122°59′W and a weaker appearance of cyclonic flow in the northwest part of the survey area centered around 37°00′N, 123°13′W. At the western boundary, anticyclonic flow was centered at 36°18′N, 123°40′W. When combined with adjacent cyclonic features, strong offshore flow occurred through the western boundary at 36°36′N and southward flow out of the survey area at 36°N.

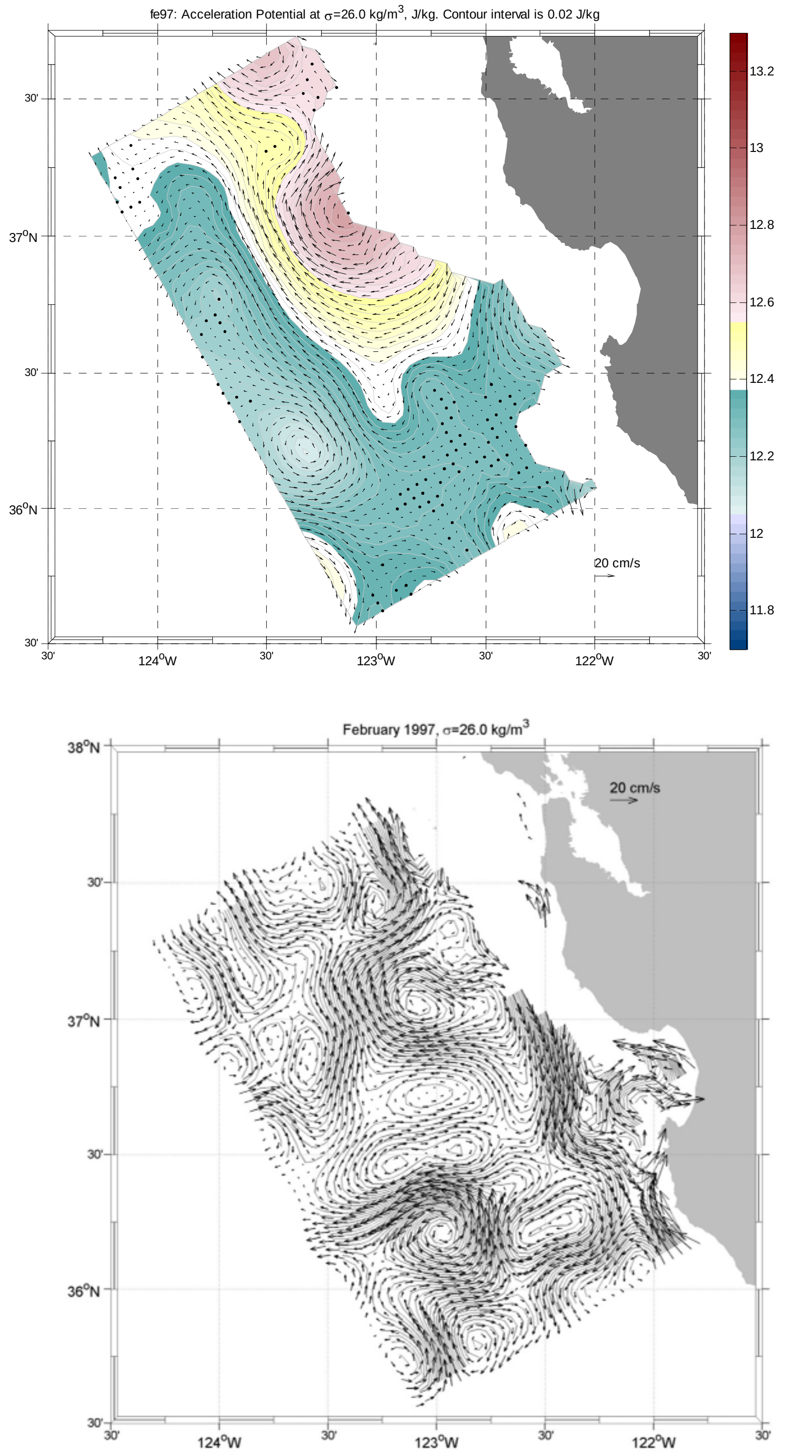


Figure 17. Acceleration potential in J/kg during February 1997 (upper) and ADCP velocities in cm/s (lower) for the 26.0 kg/m^3 density surface. Contour interval is 0.02 J/kg (upper) and the magnitude of flow is given by the arrow shown in the upper right corner (lower).

Figure 18 displays acceleration potential on the 26.8 kg/m^3 isopycnal. Cyclonic flow was observed at the same location seen on the 26.0 kg/m^3 isopycnal (centered near 37°03´N, 123°28´W and 36°15´N, 123°03´W). Inshore poleward flow continued on the 26.8 kg/m^3 isopycnal with speeds similar to that of the flow seen on the 26.0 kg/m^3 isopycnal, 20-30 cm/s. A smaller anticyclonic flow occurred near 36°18´N, 123°36´W, resulting in onshore flow across the pressure ridge at 36°-30´N, 123°-45´W..

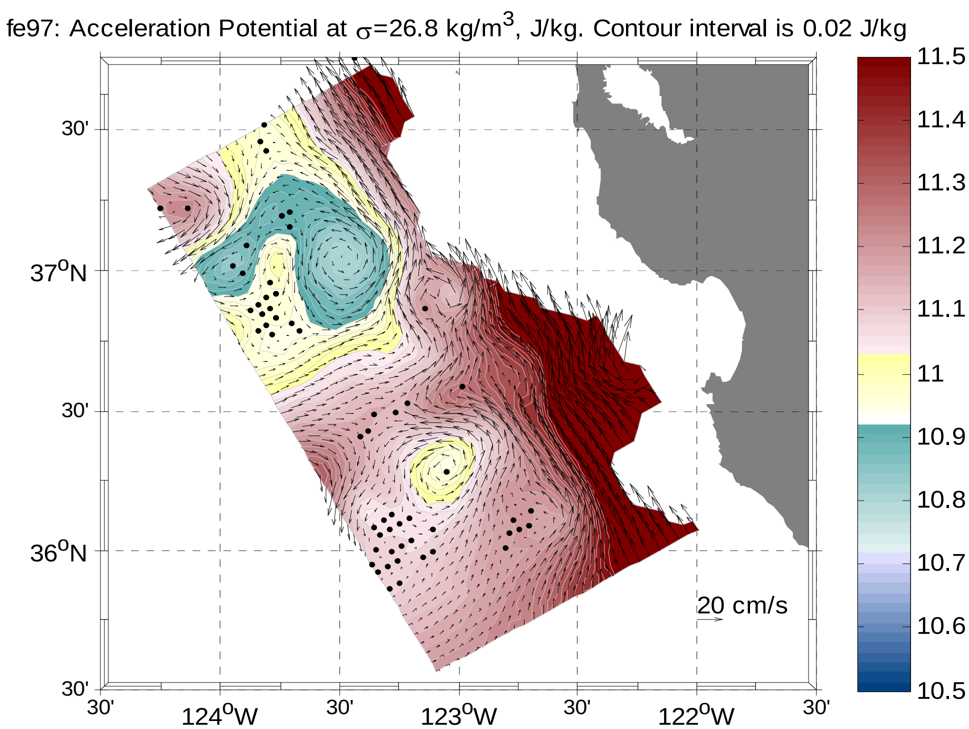


Figure 18. Acceleration potential J/kg during February 1997 on the 26.8 kg/m^3 density surface.

5. Sea Surface Height – Geopotential and SSHA

The pattern for dynamic height (0/1000 dbar) was complex (Figure 19, upper). South of 37°N, minimum dynamic height, 12.6 J/kg, was observed next to the coast; this trough extended offshore along 36°15´N to the western edge of the survey region and thence to the northwest to 37°N. Next to the coast at 37°N, maximum dynamic height, 13.6 K/kg, occurred. The geostrophic surface flows corresponded to anticyclonic flow to the north, cyclonic to the south, and southward across the entrance to Monterey Bay.

For the daily mean sea level anomaly (MSLA) for the central cruise day (21 February) (Figure 19, lower), there appeared to be a very small sea level depression (negative MSLA) along the coast and extending off of the coast in the southern region of the survey area similar to that of the dynamic height field. A maximum sea level depression of approximately 4-5 centimeters is seen centered around 35°48´N, 122°52´W. The remainder of the survey area has a sea level elevation (positive MSLA) with a maximum of 4-5 centimeters. Maximum sea level occurred outside the survey region at 35°N, 124°45´W.

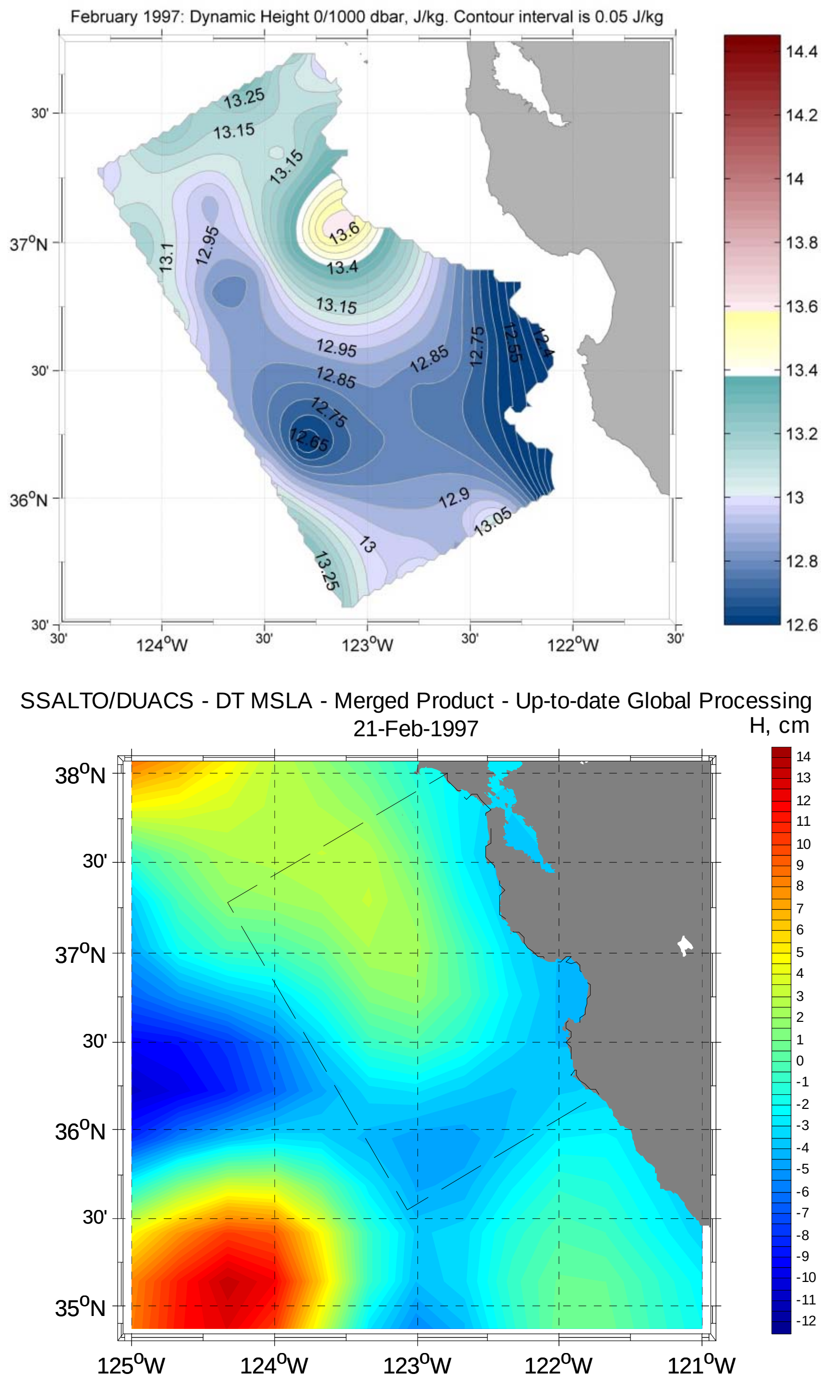


Figure 19. Geopotential (Dynamic Height) in J/kg for February 1997 from 0-1000 dbar (upper) and SSHA in cm (daily mean from 21 February). Contour interval is 0.02 J/kg. (upper) and 1 cm (lower).

B. SEPTEMBER 1997

The September 1997survey was done by R/V New Horizon, which departed Port Hueneme at 1513Z on 5 September. CTD observations began at 0135Z, 5 September, and a chart of CTD station positions is shown in Figure 20. Two 24-hour time series with CTD casts every hour were conducted, with the first commencing at 0430Z, 7 September, at 37°51.7′N, 123°03.7′W. The second commenced at 2312Z, 9 September at 37°34.8′N, 122°51.3′W, in a depth of 85 meters. CTD observations continued until 1815Z, 14 September.

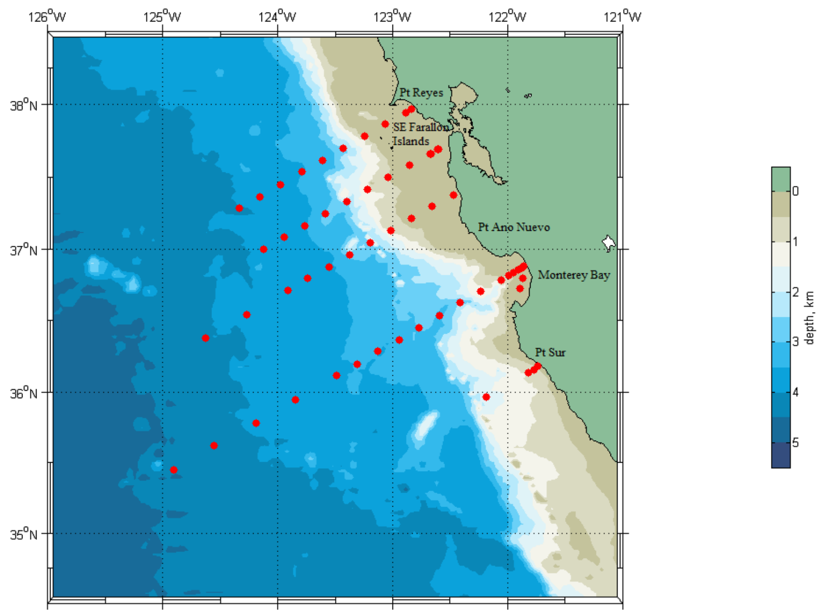


Figure 20. Station positions for September 1997 (shown by red dots).

1. T/S Diagram

The range of spiciness and associated water properties observed for the September 1997 cruise is shown by the black dots in figure 21. Spiciness (potential temperature, salinity) ranged from approximately -0.05 kg/m^3 (9.0°C, 33.65) to 0.25 kg/m^3 (10.3°C, 33.80) on the 26.0 kg/m^3 density surface. For the deeper 26.8 kg/m^3 density surface, spiciness (potential temperature, salinity) ranged from -0.20 kg/m^3

(6.3°C, 34.10) to 0.10 kg/m^3 (7.1°C, 34.25). Surface waters were as warm as 19°C with maximum salinity of 33.5. Between 6-8°C, water properties appeared to be about as equal to 0.1 greater than the mean.

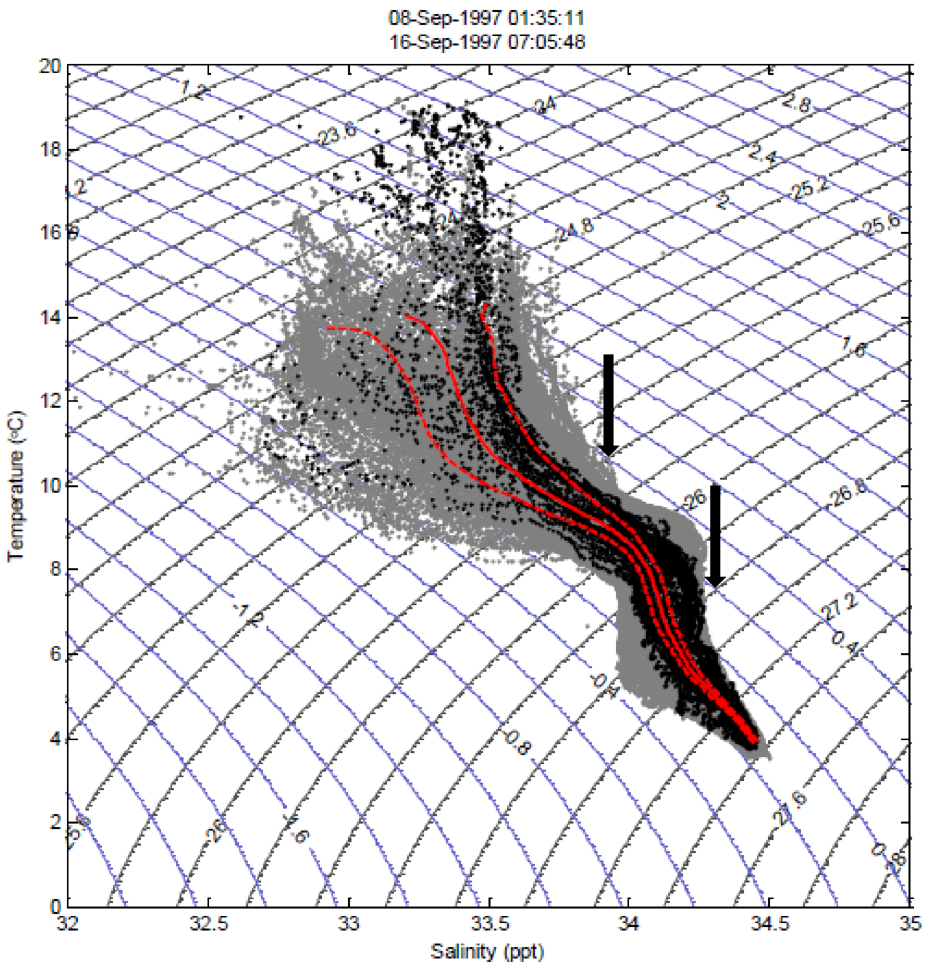


Figure 21. T/S Diagram for September 1997. . Black dots are data from the September 1997 cruise, and grey dots represent data from all 10 NAVO cruises. The solid (dashed) red line is the mean (± one standard deviation) of salinity as a function of potential temperature for all 10 NAVO cruises. Density anomalies are shown on the curved lines that slope upward to the right and spiciness is shown by the curved lines that slope downward to the right. Black arrows designate 26.0 and 26.8 kg/m^3 density surfaces.

2. Pressure

Pressure on the 26.0 kg/m^3 isopycnal showed a shallow ridge in the middle of the survey region near latitude 36-37°N and 122°-15′W-124°-00′W (Figure 22, upper). The pressure here ranges between 90.88 and 114 dbar. The maximum pressure levels were seen in the northeast, with the depressed 26.0 kg/m^3 isopycnal having a maximum pressure of 143.80 dbar. On the 26.8 kg/m^3 isopycnal, the minimum pressure observed was approximately 371.87 dbar (Figure 22, lower). The pressure ridge extended in a northwest to southeast direction from 37°15′N, 124°15′W to 36°30′N, 122°30′W. Deepest pressures, greater than 440 dbar, were found to the north of the pressure ridge.

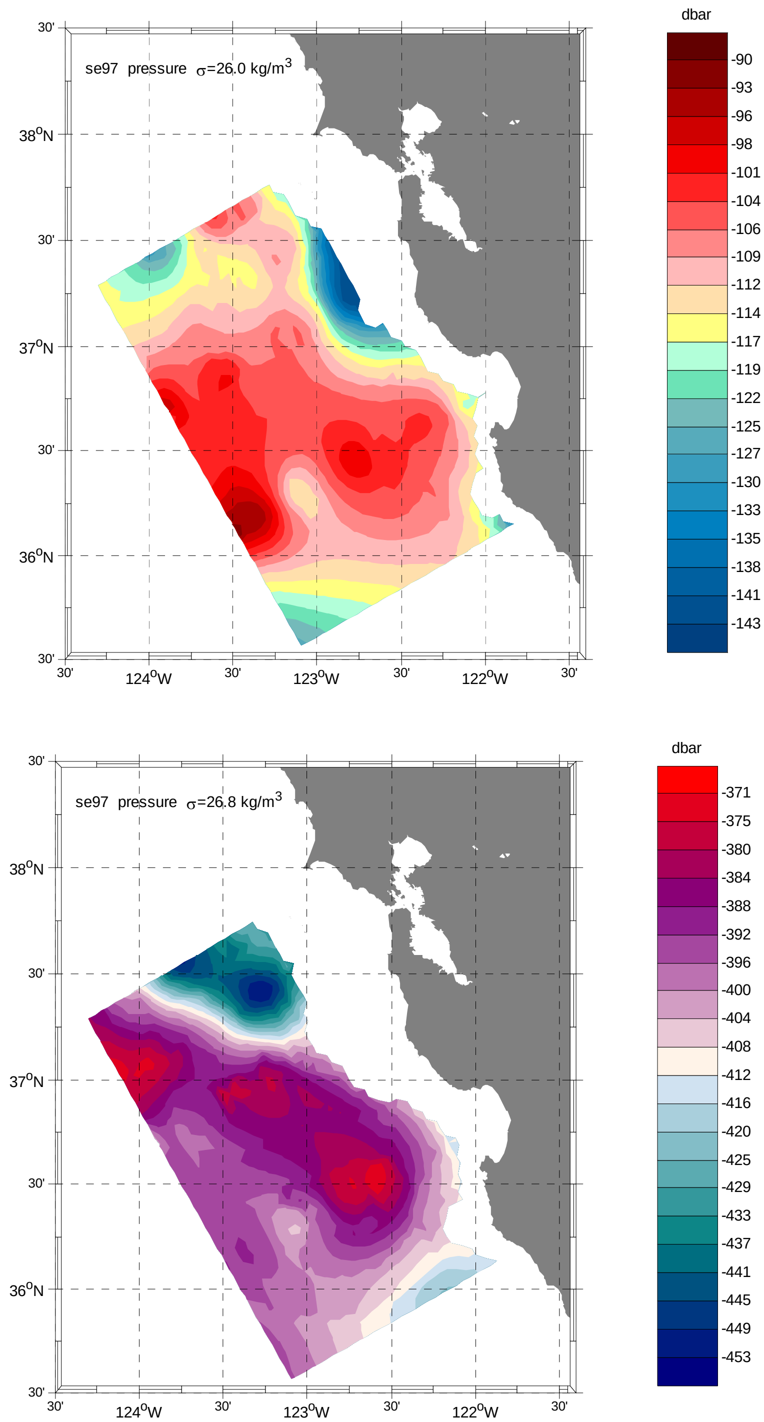
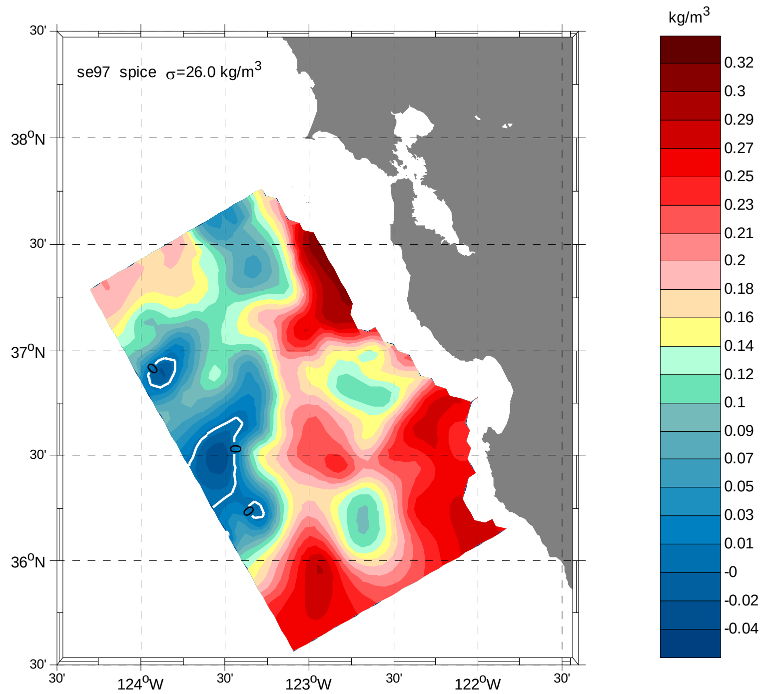


Figure 22. Pressure in dbar during September 1997 for the 26.0 kg/m^3 (upper) and 26.8 kg/m^3 density surfaces (lower). Contour interval is 2.6 dbar (upper) and 4.1 dbar (lower).

3. Spiciness

In Figure 23 (upper), minimum spiciness, less than 0.15 kg/m^3, on the 26.0 kg/m^3 isopycnal, occurred west of 123°W with lowest spiciness -0.046 kg/m^3. Maximum spiciness of 0.317 kg/ kg/m^3occurred in the northeast, in the same region of maximum pressure observed in the previous figure. Slightly higher values were found to the south, both next to coast between Monterey Bay and Pt. Sur, but also offshore in the southernmost part of the survey. Spiciness ranged between 0.18 and 0.31 kg/m^3 east of 123°W.

There was a distinct separation on the 26.8 kg/m isopycnal (Figure 23, lower) between regions of maximum and minimum spiciness. Minimum spiciness was seen to the west, with a minimum of -0.170 $kg/m^3$and a range between -0.170 kg/m^3 and -0.01 kg/m^3. The region of minimum spiciness to the west was separated from the region of higher spiciness closer to the coast by the zero spiciness contour, oriented north to south between 123°W and 123°30´W. The maximum spiciness was seen in the eastern region with largest values near to the coast, approximately 0.210 kg/m^3. There were some isolated boluses of near zero spiciness levels within the eastern region of the survey. Overall, spiciness in this region ranged between 0.02 kg/m^3 and 0.21 kg/m^3.



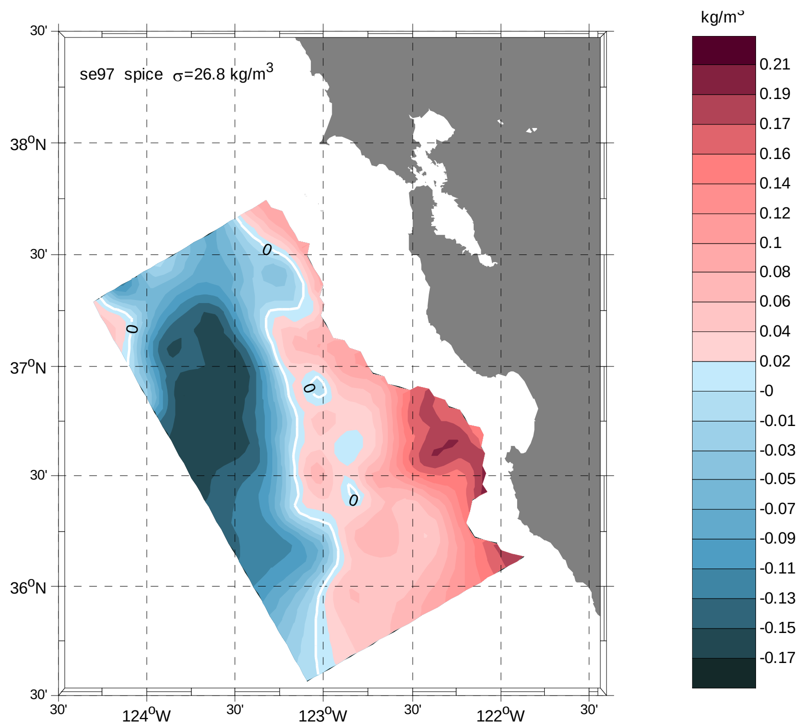


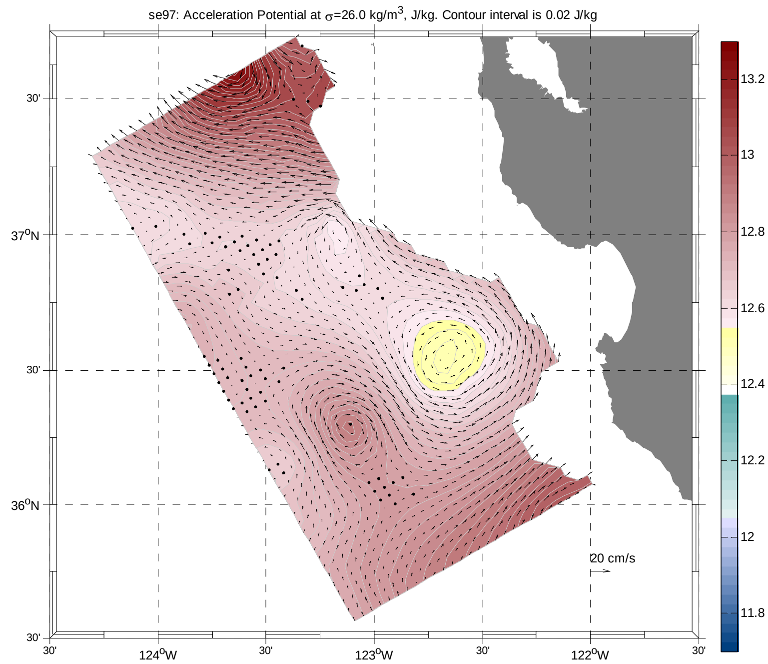
Figure 23. Spiciness in kg/m^3 during September 1997 for the 26.0 kg/m^3 (upper) and 26.8 kg/m^3 (lower) density surfaces. Contour interval is 0.018 kg/m^3 (upper) and .019 kg/m3 (lower). White denotes zero spiciness contour.

4. Acceleration Potential and ADCP

In Figure 24 (upper), acceleration potential on the 26.0 kg/m^3 isopycnal indicated a cyclonic eddy centered offshore Monterey Bay at 36°32′N, 123°37′W, adjacent to a anticyclonic eddy which was further to the west at 36°15′N, 123°05′W. Maxima of dynamic height occurred inshore along the northern and southern boundaries of the survey region so that flow was directed onshore at Point Sur and offshore near Point Reyes. A weak trough of acceleration potential extended offshore to the west-northwest of the cyclonic eddy adjacent to Monterey Bay. Poleward flow occurred along the northern side of this trough with equatorward flow on the southern side of the trough.

The ADCP field shown in Figure 24 (lower) revealed generally poleward flow inshore. Moving southwest, there were two cyclonic flow features visible offshore. Along the western boundary, this shifted to anti-cyclonic. This eddy-like flow from ADCP data offshore was evidence of the dynamic character of the transition zone offshore.

Acceleration potential along the 26.8 kg/m^3 isopycnal is shown in Figure 25. Strong poleward flow was continuous along the coast as also occurred on the 26.0 kg/m^3 isopycnal. Southwest of this flow, moving away from the coast, there is no dominate flow feature as the flow meanders in different directions. Offshore, south of 36°N, flow was poleward. North of 36°N, a series of cyclonic and anticyclonic features occurred along the offshore boundary of the survey region.



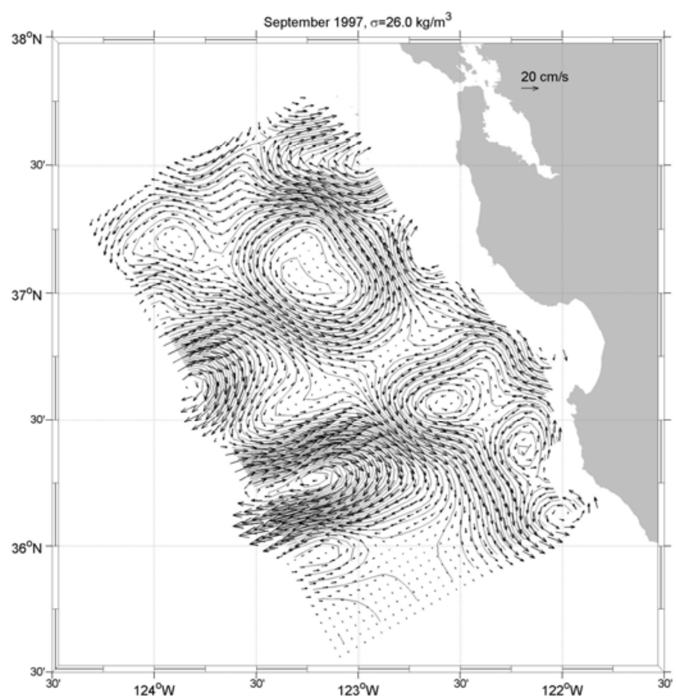


Figure 24. Acceleration potential in J/kg during September1997 (upper) and ADCP velocities in cm/s (lower) for the 26.0 kg/m^3 density surface. Contour interval is 0.02 J/kg (upper) and the magnitude of flow is given by the arrow shown in the upper right corner (lower).

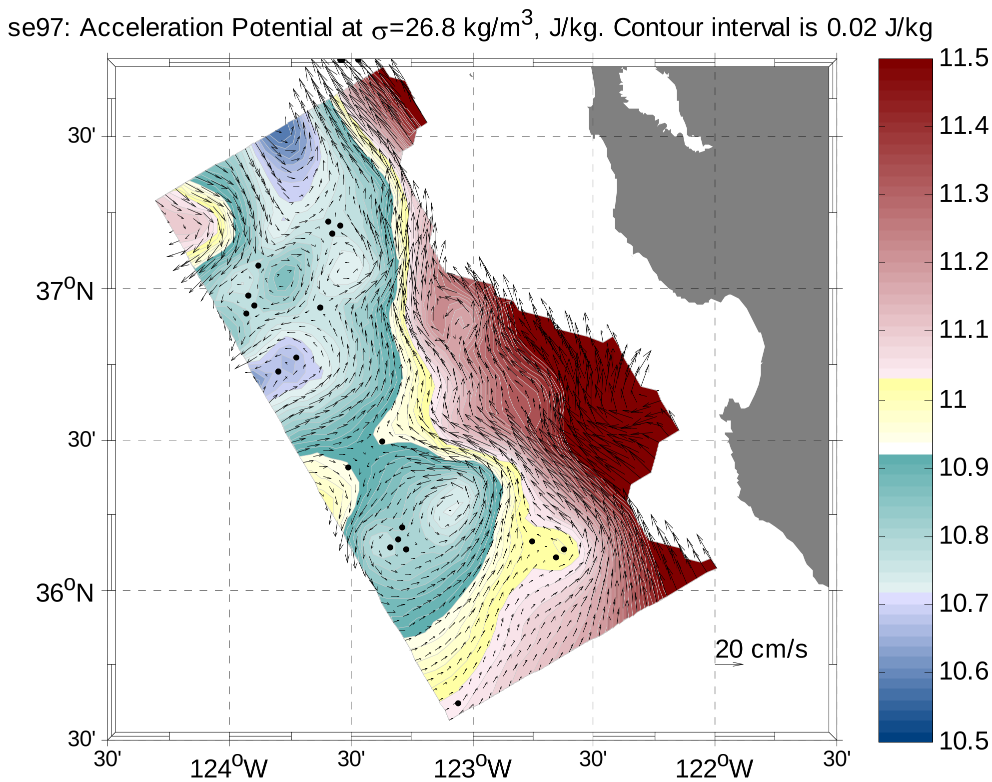


Figure 25. Acceleration potential in J/kg during September 1997 on the 26.8 kg/m^3 density surface. Contour interval is 0.05 J/kg

5. Sea Surface Height – Geopotential and SSHA

Geopotential, displayed in Figure 26 (upper), was largest along the northwest and southeast edges of the survey area. North of 37°N, isosteres were oriented east-west with values decreasing to the south, evidence of northwestward flow in this region. Eddy-like features were visible along CalCOFI line 67, in part due to lack of data. The higher values of geopotential in the southeast part of the survey region flow towards the coast in this region.

Figure 26 (lower) showed daily mean sea level anomaly (obtained from AVISO) from the median cruise date of 12 September 1997. During this month, the entire survey area experienced an elevation in sea level. The magnitude of sea level elevation increased from 5 centimeters at the coast, to ~11 centimeters in the western region of the survey area. There was good agreement with the large scale pattern of dynamic height as well as the magnitude of the ridge to trough height differences (about 5–6 centimeters).

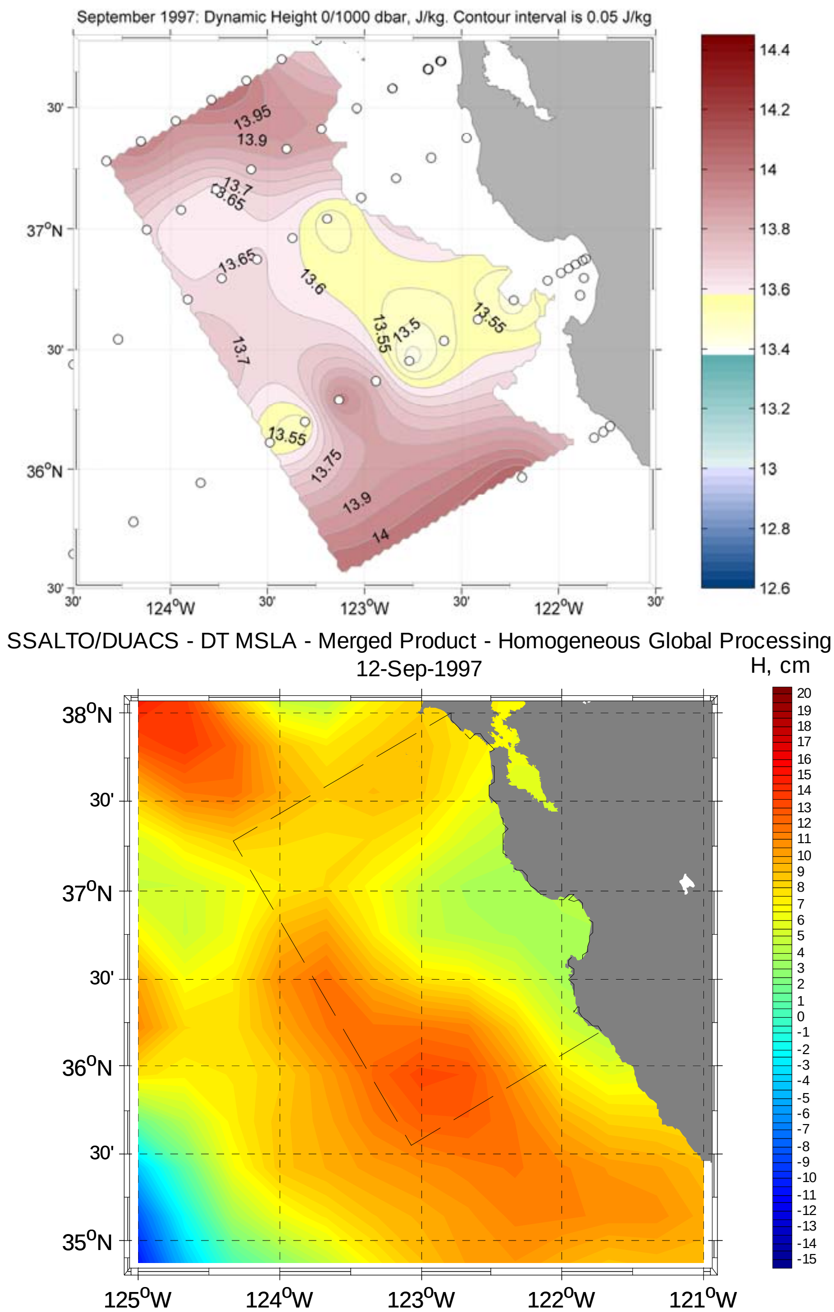


Figure 26. Geopotential (Dynamic Height) in J/kg for September 1997 from 0-1000 dbar (upper) and SSHA in cm (daily mean from 12 September). Contour interval is 0.02 J/kg. (upper) and 1 cm (lower).

C. MAY 1998

This survey was done by *R/V New Horizon*, which departed Port Hueneme at 1752Z on 28 April. CTD observations began at 0238Z, 30 April at 37°47.16´N, 123°14.60´W at depth of 120 m, and a chart of CTD station positions is shown in Figure 27. Four 24-hour time series were conducted. The first began at 0015Z, 2 May, at 37°46.49´N, 123°13.24´W, in depth of 109 m. The second began at 0342Z, 3 May, at 37°31.83´N, 122°56.34´W, in depth of 113 m. The third began at 1838Z, 6 May, at 37°17.75´W, 122°39.13´W, at depth of 90 m. The final CTD time series began at 0554Z, 8 May, at 36°56.69´N, 122°15.92´W at depth of 91 m. CTD observations continued until 1406Z, 16 May.

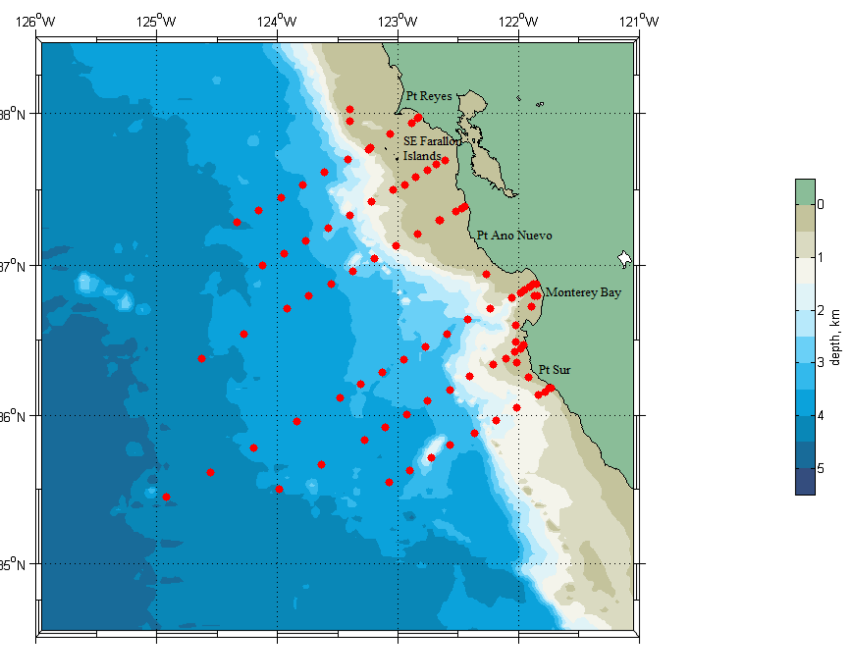


Figure 27. Station positions for May 1998 (shown by red dots)

1. T/S Diagram

The range of spiciness and associated water properties observed for the May 1998 cruise is shown by the black dots in Figure 28. Spiciness (potential temperature, salinity) ranged from approximately 0.00 kg/m^3 (9.5°C, 33.65) to 0.20 kg/m^3 (10.3°C, 33.75) on the 26.0 kg/m^3 density surface. For the deeper 26.8 kg/m^3 density surface, spiciness (potential temperature, salinity) ranged from -0.25 kg/m^3 (5.8°C, 34.00) to 0.05 kg/m^3 (7.2°C, 34.20. Sea surface temperatures were about 14.5°C and sea surface salinities ranged from 32.8 to 33.2. The salinity associated with the 6–8°C thermocline was 34.1, indicating the greater influence of Subarctic Intermediate waters for this cruise.

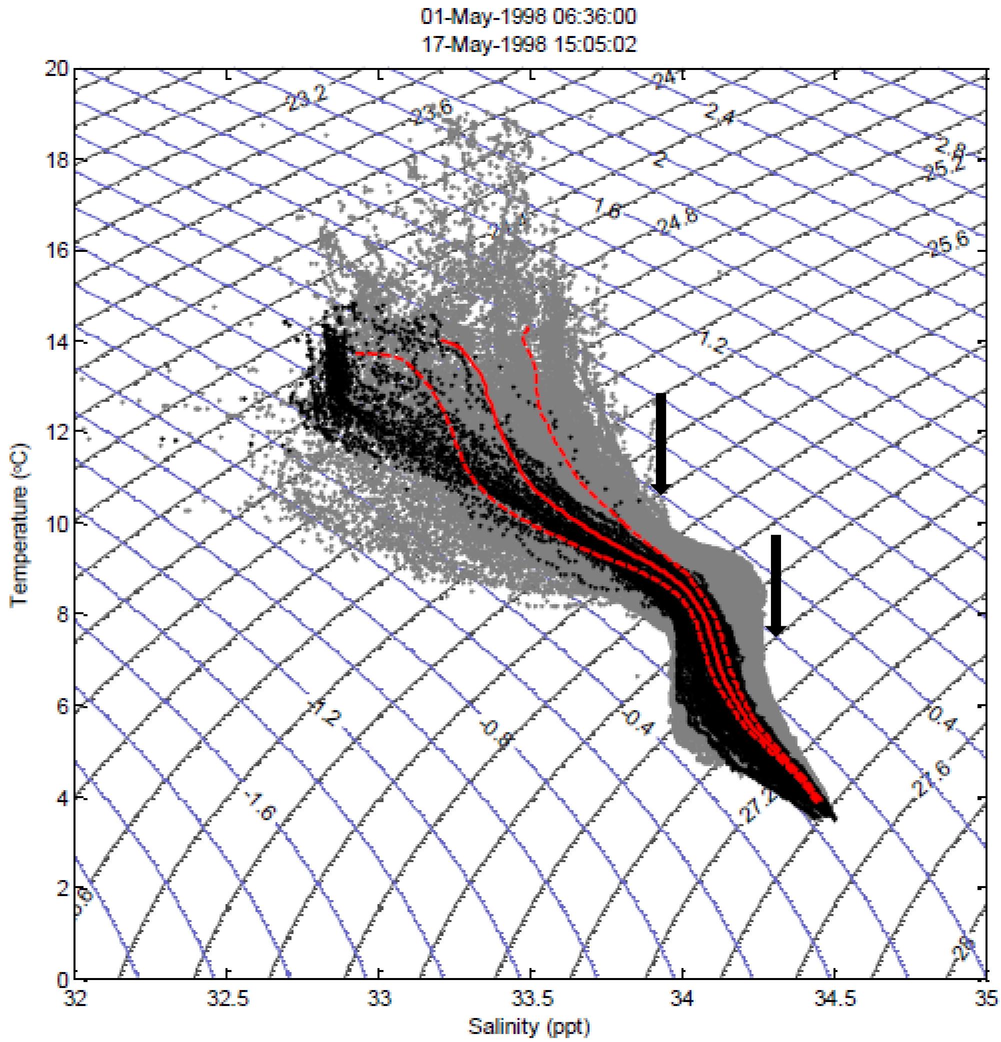


Figure 28. T/S Diagram for May 1998. Black dots are data from the May 1998 cruise, and grey dots represent data from all 10 NAVO cruises. The solid (dashed) red line is the mean (± one standard deviation) of salinity as a function of potential temperature for all 10 NAVO cruises. Density anomalies are shown on the curved lines that slope upward to the right and spiciness is shown by the curved lines that slope downward to the right. Black arrows designate 26.0 and 26.8 kg/m^3 density surfaces.

2. Pressure

Figure 29 (upper) displays pressure on the 26.0 kg/m^3 isopycnal. Contours were distinctly aligned parallel to the coastline. The minimum pressure of approximately 40.91 dbar is seen in the southeast corner of the survey area. Extending outward from the coast, pressure steadily increases to a maximum of 155 dbar. Isopycnals generally sloped upwards toward the coast, and the largest gradients of pressure change occurred near the coast.

For pressure on the 26.8 kg/m^3 isopycnal, the ridge of minimum pressure was seen inshore, extending from the northern edge of the survey area, where a distinct minimum, 294 dbar, was located at 37°21´N, 123°22´W (Figure 29, lower). The minimum extended southward along the coast at a pressure of 350 dbar but terminated offshore central Monterey Bay (~36°40´N). There is a fairly steep increase in pressure to the southwest of the pressure minimum to the location of the maximum pressure, approximately 417 dbar, centered at 36°50´N, 123°45´W. There is a smaller area of similar high pressure in the southeast region of the survey area in the vicinity of 36°13´N, 122°30´W. Note that the range of pressure change on the two density surfaces was similar, 110 dbar, and they both sloped upward toward the coast.

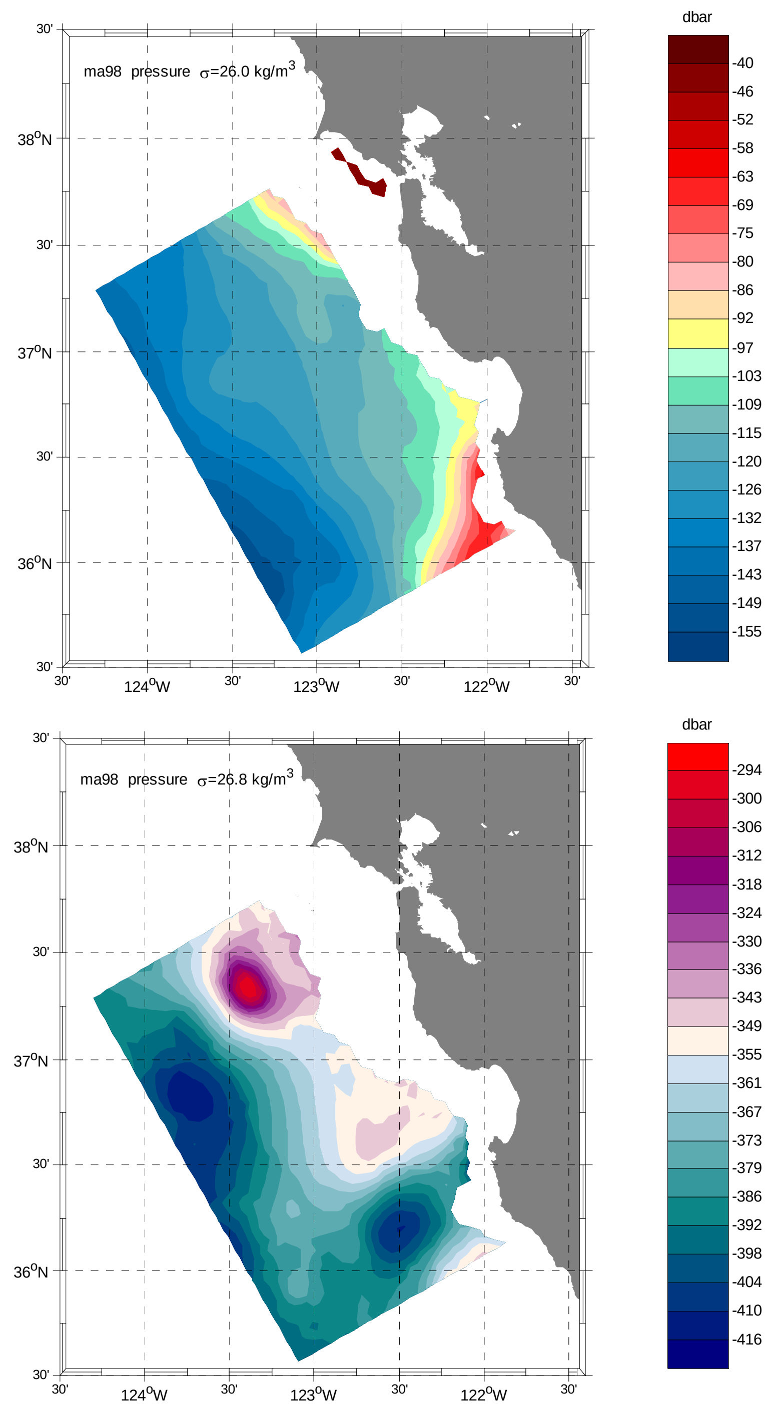


Figure 29. Pressure in dbar during May 1998 for the 26.0 kg/m^3 (upper) and 26.8 kg/m^3 density surfaces (lower). Contour interval is 5.75 dbar (upper) and 6.10 dbar (lower).

3. Spiciness

In the display of spiciness, the region of maximum spiciness on the 26.0 kg/m^3 isopycnal is seen in the southwest part of the region (Figure 30, upper). All spiciness levels are above zero in this figure. On the 26.8 kg/m^3 isopycnal, the zero spiciness contour follows a path that separates a region of predominately positive spiciness in the eastern portion of the survey area from one of largely negative spiciness to the west.

Spiciness on both density surfaces was characterized by an east-west gradient with higher spiciness waters to the east. For the 26.0 kg/m^3 isopycnal, spiciness of 0.2 kg/m^3 followed the 123°12´W meridian. The shallow density surface contained a number of mesoscale features with highest spiciness along the coast near Pt. Sur. The deeper density surface had a distinct minimum, -0.18 kg/m^3, at 36°40´N, 123°40´W (130 km west of Monterey Bay); at the same latitude but immediately offshore Monterey Bay, maximum spiciness, 0.25 kg/m^3, was observed,

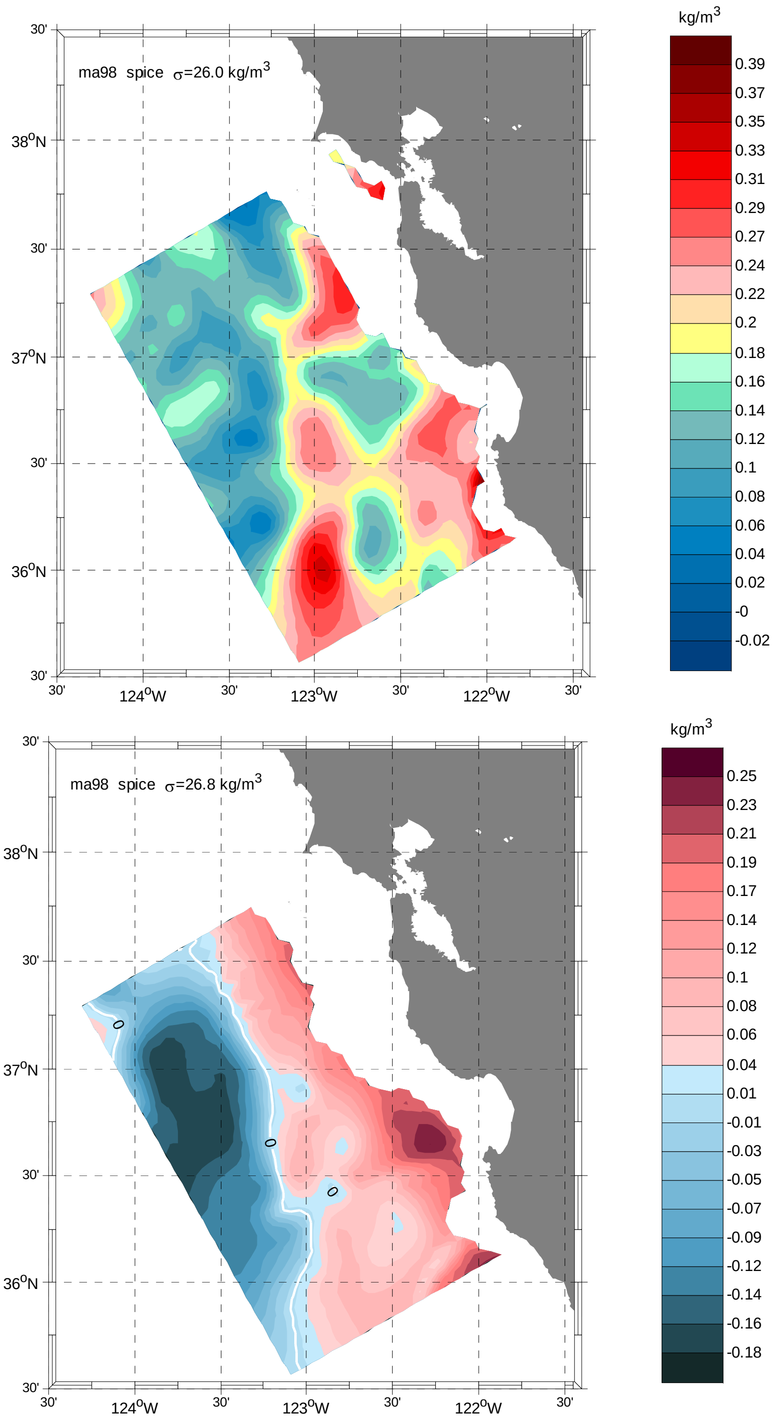


Figure 30. Spiciness in kg/m^3 during May 1998 for the 26.0 kg/m^3 (upper) and 26.8 kg/m^3 (lower) density surfaces. Contour interval is 0.021 kg/m^3 (upper and lower). White denotes zero spiciness contour.

4. Acceleration Potential and ADCP

Isosteres of acceleration potential on the 26.0 kg/m^3 isopycnal (Figure 31, upper) were parallel to the coast except at the southern boundary where the minimum acceleration potential, 11.5 J/kg, occurred inshore. The monotonic increase of acceleration potential from maximum offshore to minimum at the coast corresponded to equatorward flow. Several weak mesoscale features existed: anticyclonic on the western boundary at 36°05´N, 123°08´W and 36°35´N, 123°50´W, cyclonic flow at 37°22´N, 123°27´W.

The ADCP field is also shown in Figure 31 (lower). There was general southward and eastward flow visible in the same location (36°52´N, 123°47´W) where an anti-cyclonic surrounded by cyclonic flow occurred on the acceleration potential figure. A similar situation occurred in the vicinity of 36°05´N, 123°00´W. ADCP velocities showed sporadic flow northward along the eastern portion of the survey region.

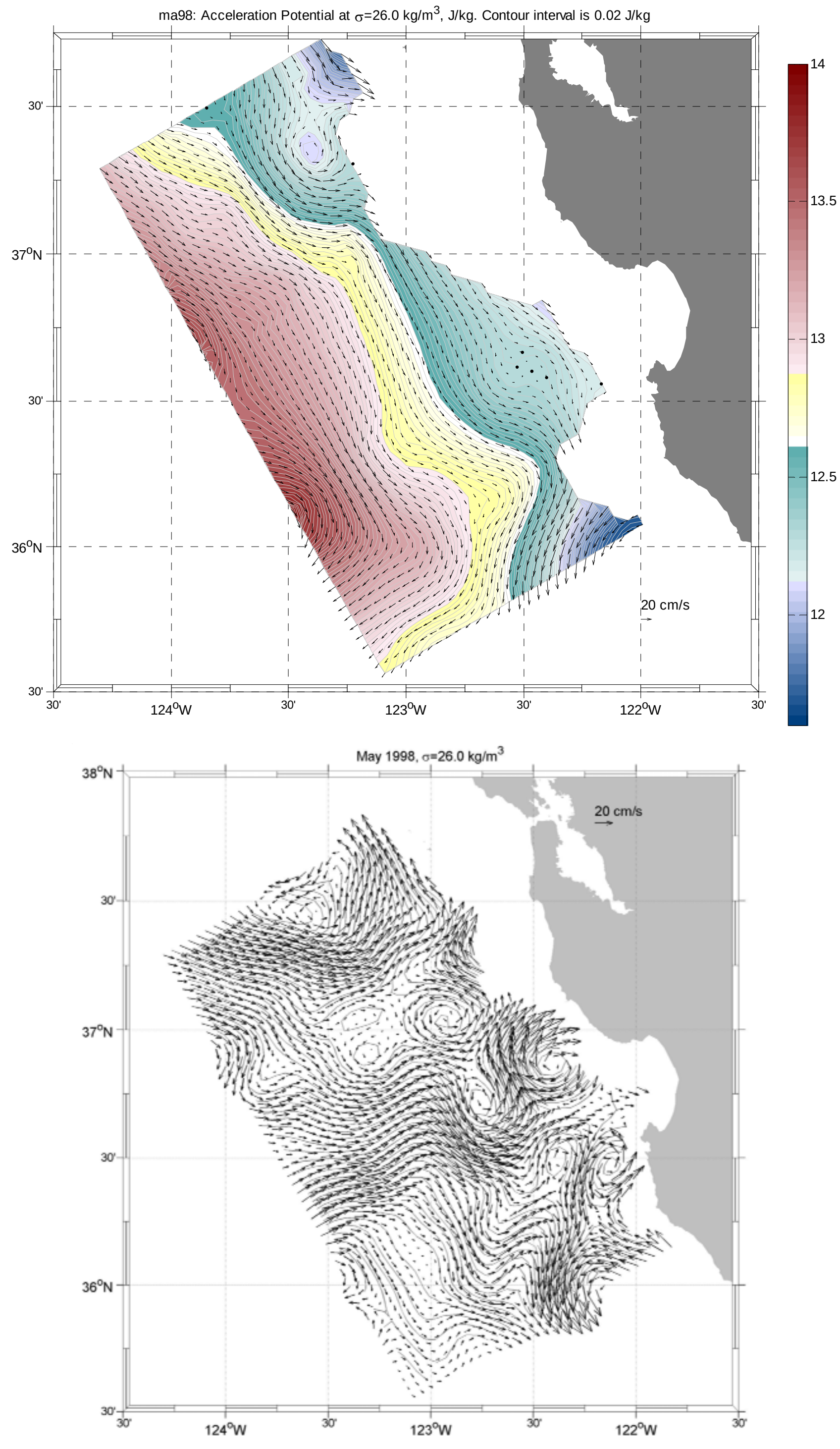


Figure 31. Acceleration potential in J/kg during May 1998 (upper) and ADCP velocities in cm/s (lower) for the 26.0 kg/m^3 density surface. Contour interval is 0.02 J/kg (upper) and the magnitude of flow is given by the arrow shown in the upper right corner (lower).

Acceleration potential on the 26.8 kg/m^3 isopycnal showed three distinct areas of cyclonic flow (Figure 32). The strongest of the three occurs in the vicinity of 36-07°N, 122-35°W, in the midst of the strong poleward flow of the inshore countercurrent. Cyclonic flow also occurred near 36°45′N, 123°45′W and 36°07′N, 123°22′W. Poleward flow extended across a wide portion of the survey area in this figure.

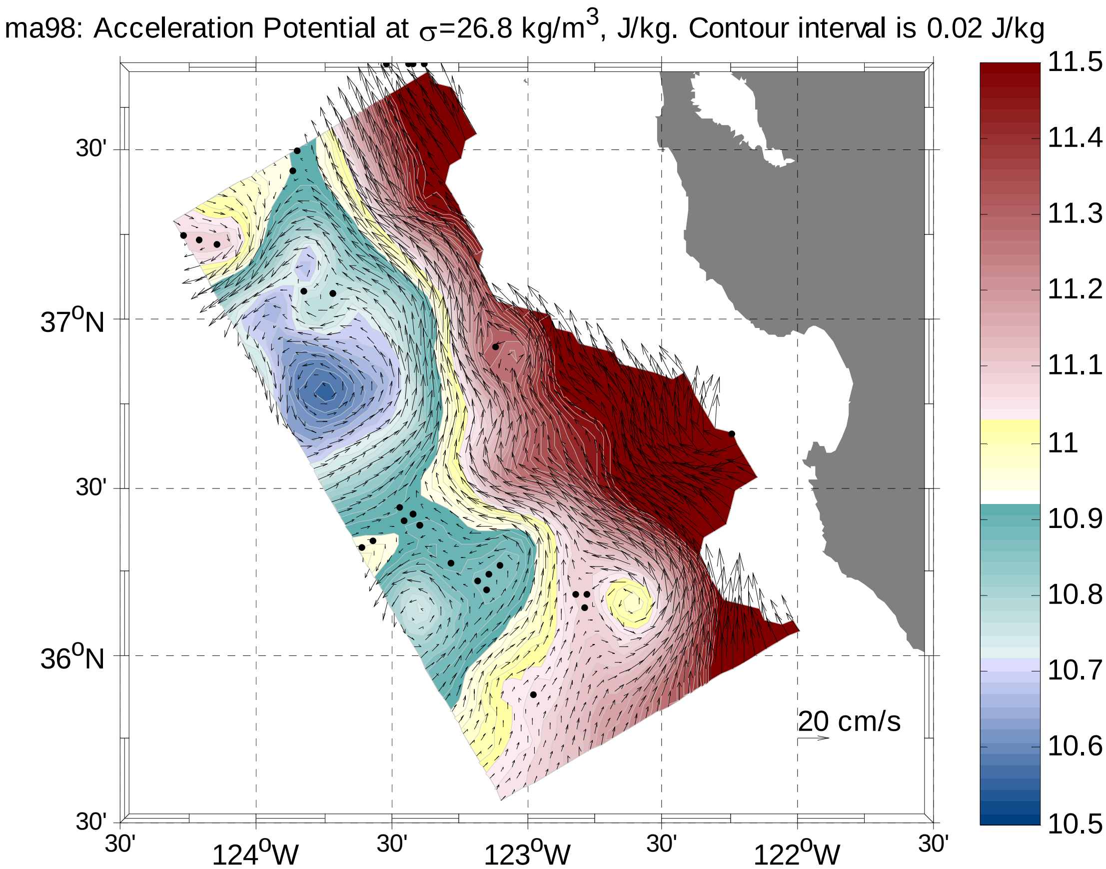
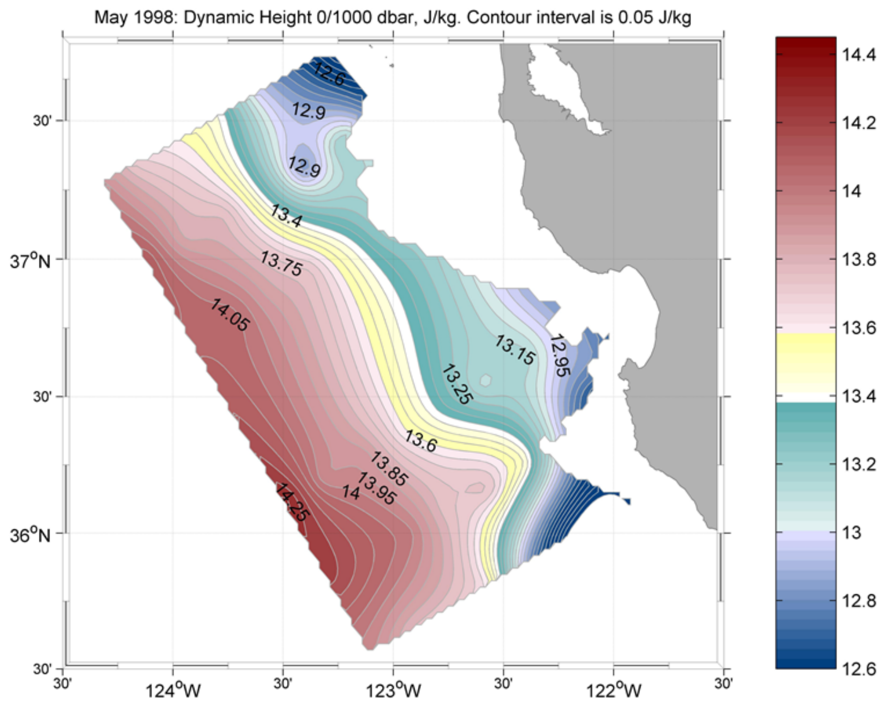


Figure 32. Acceleration potential in J/kg during September 1997 on the 26.8 kg/m^3 density surface. Contour interval is 0.05 J/kg

5. Sea Surface Height – Geopotential and SSHA

In Figure 33 (upper), isolines of dynamic height were generally oriented parallel to the coast. Dynamic height increased offshore, from a minimum of ~12.8 J/kg to ~14.3 J/kg in several places along the western edge. This suggested equatorward flow through the survey area.

MSLA in Figure 33 (lower) (for May 8) showed sea level increasing offshore. Near to the coast, sea level was depressed -2 to -4 cm, with the exception of an intrusion of near zero MSLA extending into the Monterey Bay. MSLA steadily increased offshore with a maximum of seven to eight centimeters of sea level elevation along the western edge of the survey area. The total range of MSLA was 12 cm compared to about 15 cm for steric height. Note too, the similarity of the alongshore sinusoid depicted by the yellow contours in both fields (Figure 33). The southern shoreward excursion was at 36°15´N.



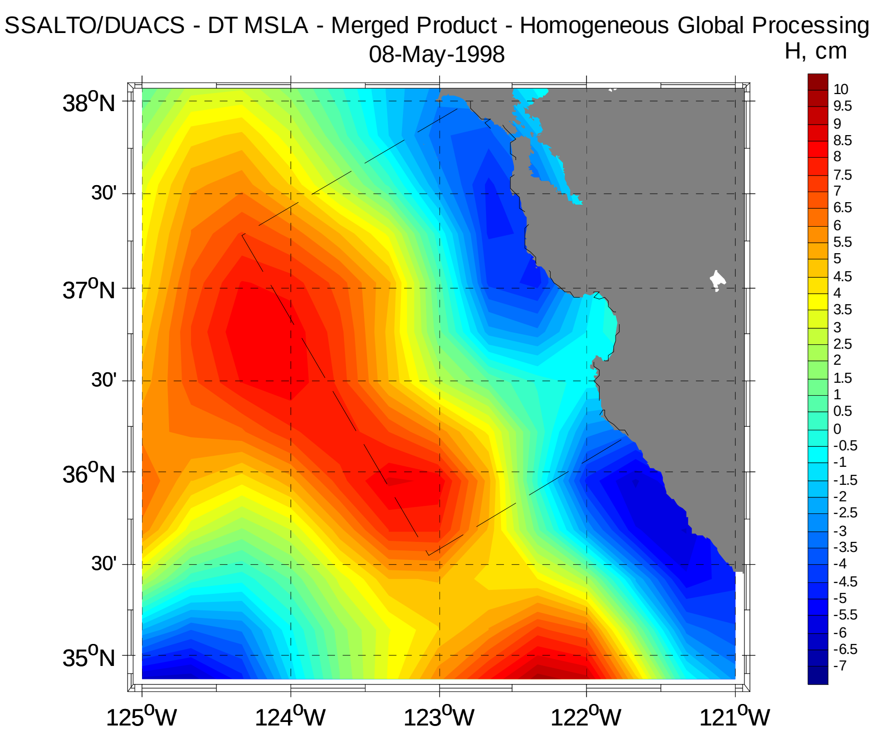


Figure 33. Geopotential (Dynamic Height) in J/kg for May 1998 from 0–1000 dbar (upper) and SSHA in cm (daily mean from 08 May). Contour interval is 0.02 J/kg (upper) and 0.5 cm (lower).

D. NOVEMBER 1998

This survey was done by *R/V New Horizon*, which departed Port Hueneme at 0200Z, 27 October. CTD observations began at 1059Z, 28 October at 37°16.55´N, 124°19.43´W and a chart of CTD station positions is shown in Figure 34. Three 24-hour time series were conducted, with the first beginning at 1000Z, 29 October, at 37°55.56´N, 122°55.30´W in depth 52 m. The second began at 0325Z, 1 November, at 37°17.79´N, 122°39.21´W, in depth of 90 m. The final time series began at 0831Z, 2 November, at 36°56.13´N, 122°18.08´W, in depth of 126 m. CTD observations continued until 1331Z, 9 November, and the vessel returned to San Diego on 11 November.

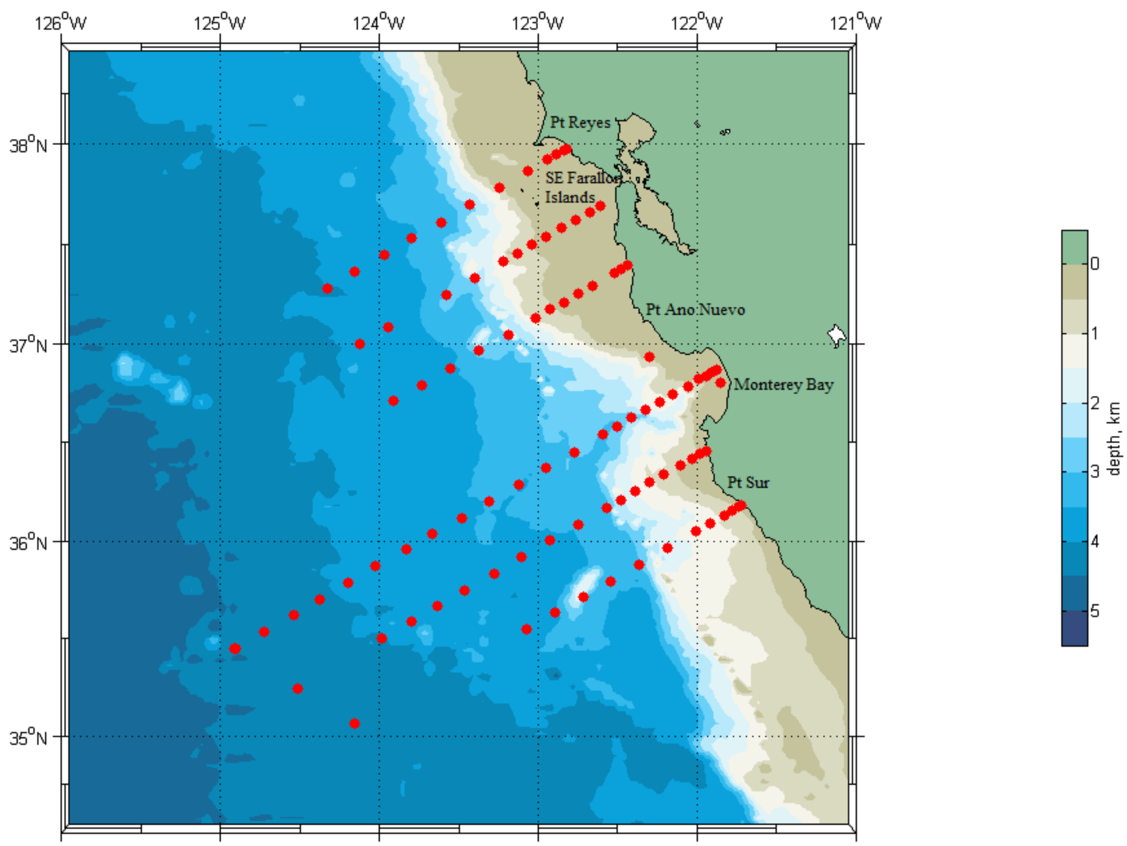


Figure 34. Station Positions for November 1998 (shown by red dots).

1. T/S Diagram

The range of spiciness and associated water properties observed for the November 1998 cruise is shown by the black dots in figure 34. Spiciness (potential temperature, salinity) ranged from approximately 0.00 kg/m^3 (9.3°C, 33.60) to 0.20 kg/m^3 (10.2°C, 33.80) on the 26.0 kg/m^3 density surface. For the deeper 26.8 kg/m^3 density surface, spiciness (potential temperature, salinity) ranged from -0.20 kg/m^3 (6.0°C, 34.05) to 0.00 kg/m^3 (6.8°C, 34.05). Maximum sea surface temperatures were about 15°C. The salinity of 6-8°C thermocline water was 34.1, slightly fresher than the mean over ten cruises.

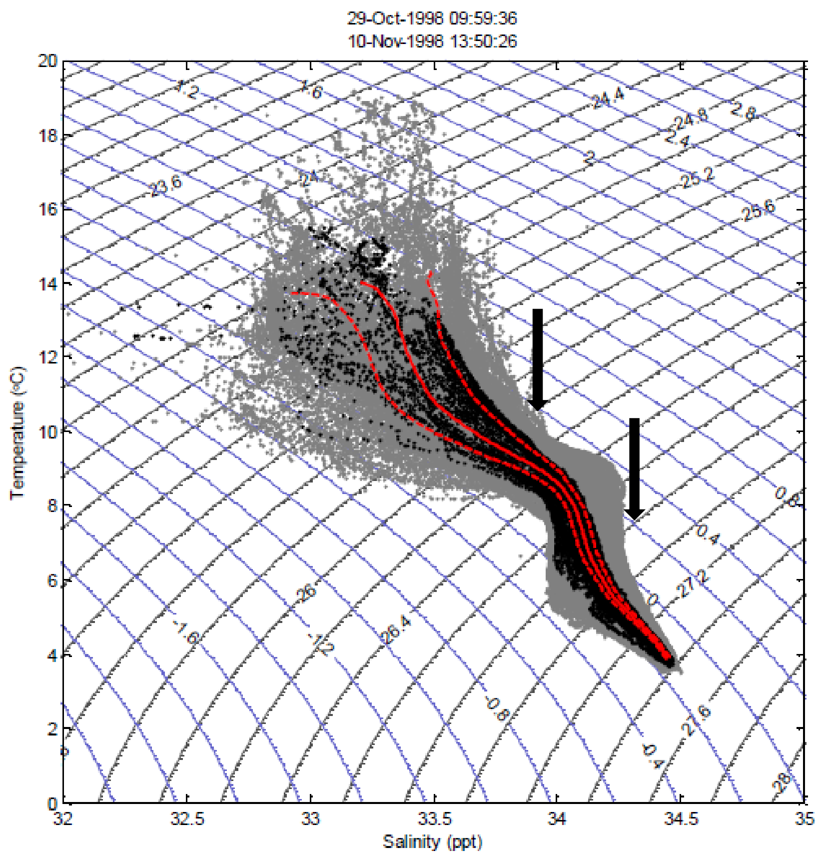


Figure 35. T/S Diagram for November 1998. . Black dots are data from the November 1998 cruise, and grey dots represent data from all 10 NAVO cruises. The solid (dashed) red line is the mean (± one standard deviation) of salinity as a function of potential temperature for all 10 NAVO cruises. Density anomalies are shown on the curved lines that slope upward to the right and spiciness is shown by the curved lines that slope downward to the right. Black arrows designate 26.0 and 26.8 kg/m^3 density surfaces.

2. Pressure

The pressure on the 26.0 kg/m^3 isopycnal showed an increasing pressure from east to west, with a minimum pressure of approximately 74 dbar occurring near to the coast (Figure 35, upper). The largest (deepest) pressure occurred in the western portion of the survey area, between 36°00´N and 36°15´N. The exception to the east-west pressure gradient was the region off of the Monterey Bay, where there was an area of pressure ranging between 102 and 109 dbar.

On the 26.8 kg/m^3 isopycnal (Figure 35, lower), relatively shallower pressure levels occurred in the northern part of the survey area, with the shallowest pressure feature (pressures below 349 dbar) near 37°17´N, 123°16´W. Deeper pressure levels occurred south and west of Monterey Bay, greater than 374 dbar, with the exception of an intrusion of a pressure ridge which extended from the north toward the southeast along 122°30´W.

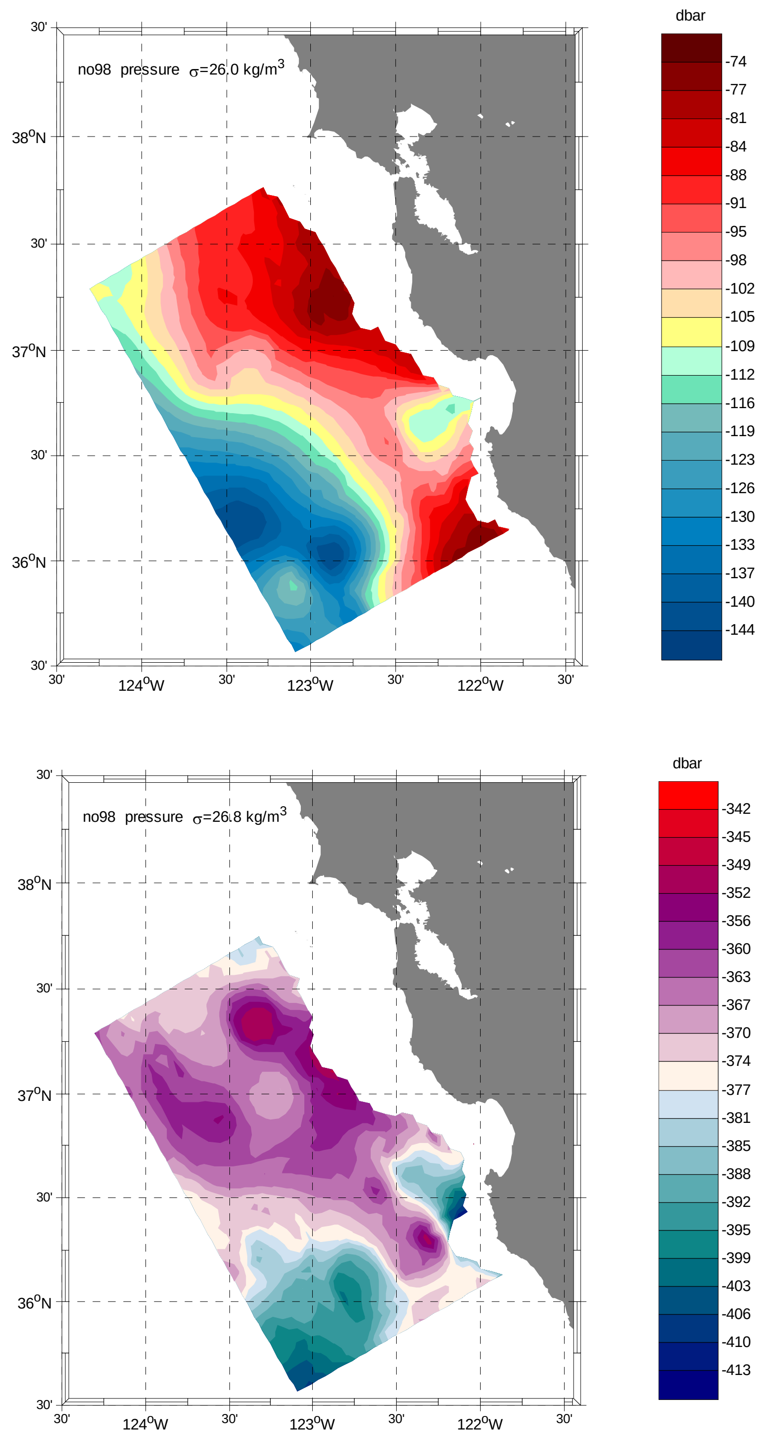


Figure 36. Pressure in dbar during November 1998 for the 26.0 kg/m^3 (upper) and 26.8 kg/m^3 density surfaces (lower). Contour interval is 3.5 dbar (upper) and 3.55 dbar (lower).

3. Spiciness

Spiciness is shown in Figure 37. On the 26.0 kg/m^3 isopycnal (Figure 37, upper) spiciness decreased towards from east to west. There were two sub mesoscale regions (less than 20 km) where spicinessd decreased to zero in the vicinity of 36°57′N, 123°48′W and 36°30′N, 123°30′W. As in previous surveys, the 0.2 kg/m^3 spiciness contour was oriented along 123°06′W, dividing higher spiciness inshore waters from lower spiciness offshore waters. Also, there were many mesoscale features on the 26.0 kg/m^3 isopycnal.

On the 26.8 kg/m^{3}isopycnal, the zero spiciness contour distinctly divided negative spiciness levels to the east of 123°W, from positive spiciness levels to the west of ~123°15′W (Figure 37, lower). There was an isolated region of zero spiciness levels in the southeast region of the survey area that corresponded to an intruding area of lower pressures seen in the previous figure.

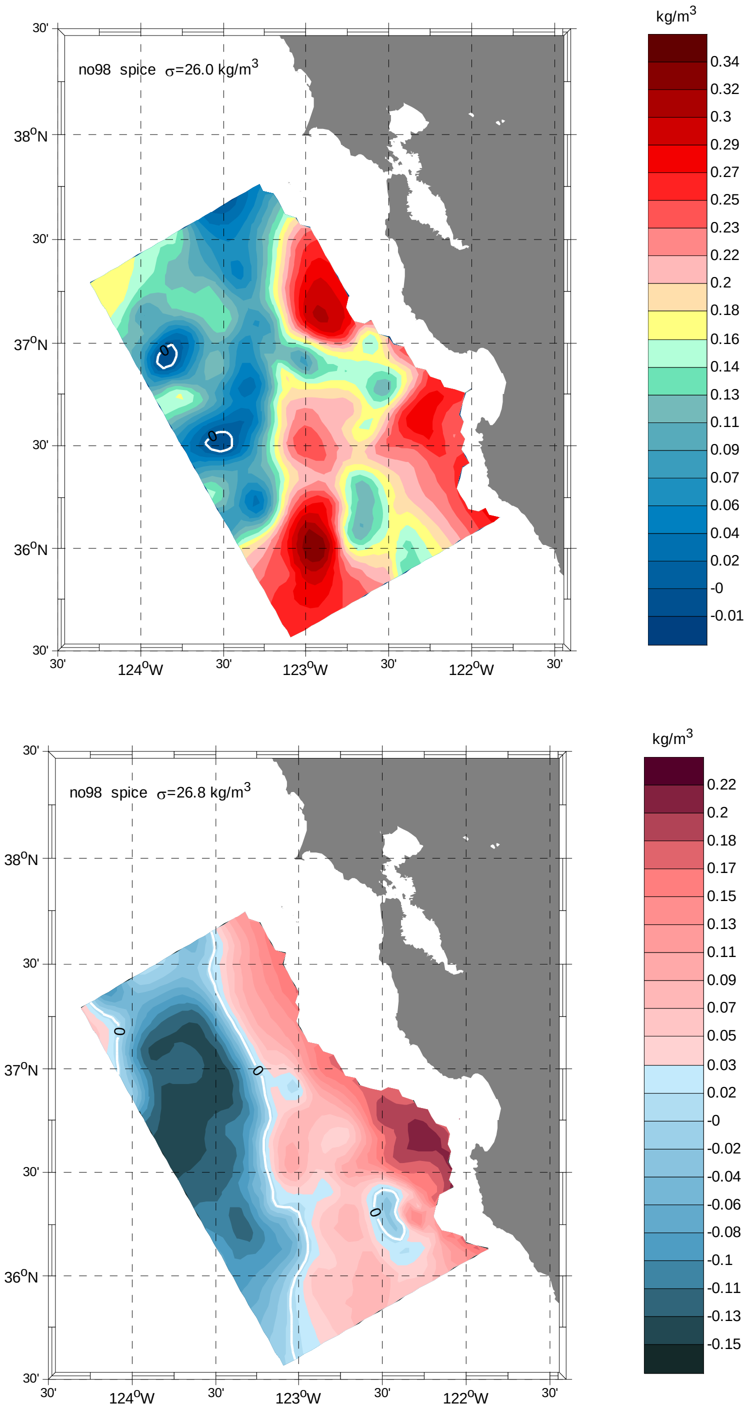


Figure 37. Spiciness in kg/m^3 during November 1998 for the 26.0 kg/m^3 (upper) and 26.8 kg/m^3 (lower) density surfaces. Contour interval is 0.017 kg/m^3 (upper) and .018 kg/m^3 (lower). White denotes zero spiciness contour.

4. Acceleration Potential and ADCP

Unlike the May 1998 survey where isosteres of acceleration potential were meridional, November 1999 isosteres for the 26.0 kg/m^3 isopycnal (Figure 38, upper) were zonal over the central and northern portion of the survey region. Acceleration potential values were greatest at 38°05´N, 122°45´W, 12.8 J/kg, and minimum near 38°00´N, 123°40´W resulting in a broad band of offshore flow over much of the survey region which turned southward at 36°15´N along 123°30´W. A mesoscale area of higher dynamic height existed off Monterey Bay, directing a portion of the eastward flow into the Bay. Note that acceleration potential increased to the north of 38°05´N, an area of offshore flow off Pt. Reyes.

ADCP velocities on the 26.0 kg/m^3 isopycnal are shown in Figure 37 (lower). Poleward flow was observed both inshore and offshore along the southern boundary of the survey region. Between these inflows, two adjacent cyclonic eddies transport flow eastward and southward. A continuous stream of poleward flow could be traced along the coast but it moved offshore, around an anticyclonic mesoscale eddy to the southwest of Pt. Año Nuevo. A cyclonic eddy occurred at the entrance to Monterey Bay. In the eastern portion of the survey between 36°30´N and 37°00´N, there is strong equatorward and westward flow in contrast to the poleward flow to the south. A series of eddy-like features along the western boundary create a complex pattern of flow there.

Figure 39 shows acceleration potential on the 26.8 kg/m^3 isopycnal, where the inshore countercurrent is visible throughout the survey area. There are two cyclonic flows on the western side of the survey area, centered at 37°00´N, 123°45´W and at 36°10´N, 123°16´W. There is a region of inflow between these two cyclonic features that begins at 36°30´N.

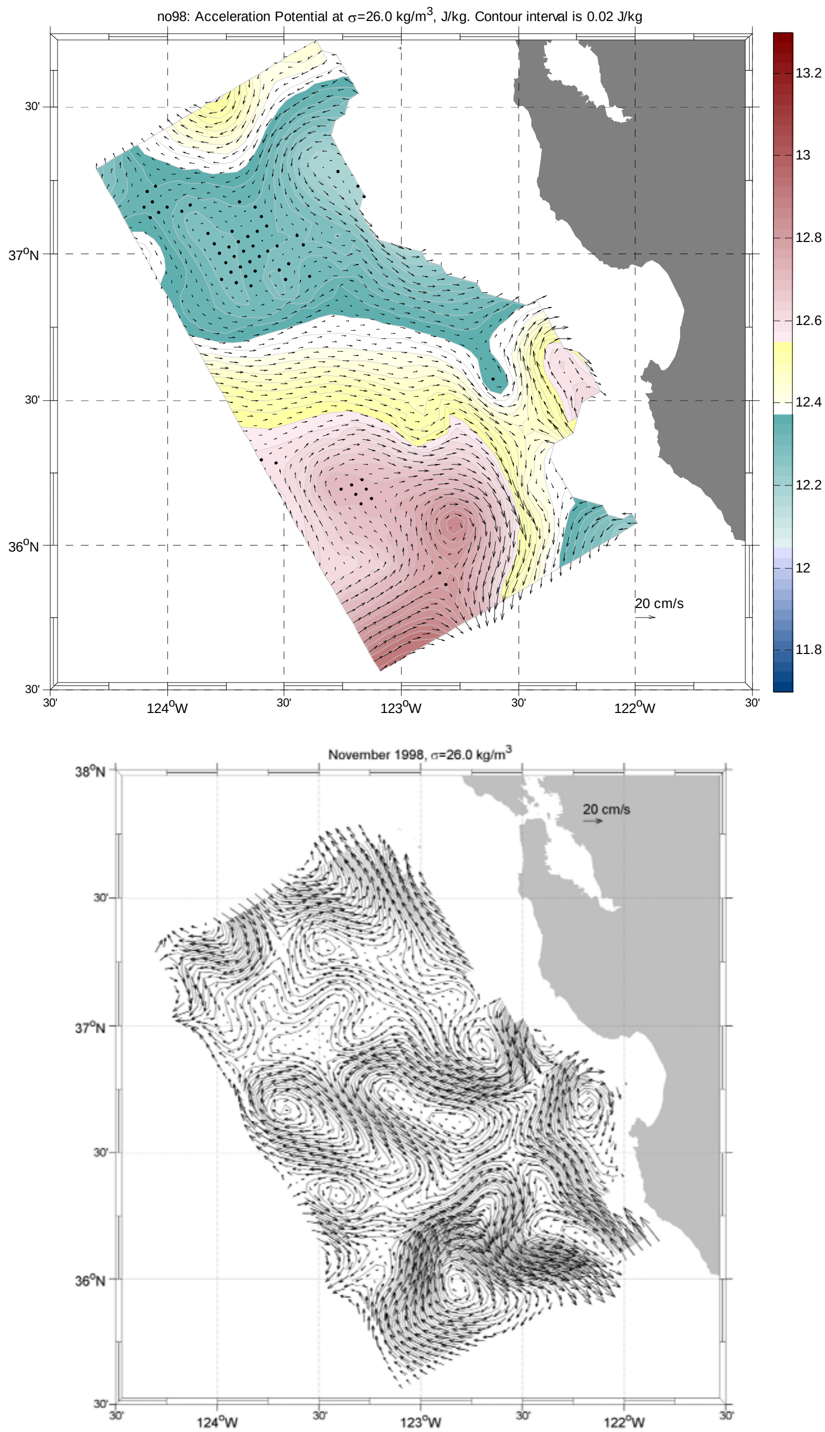


Figure 38. Acceleration potential in J/kg during November 1998 (upper) and ADCP velocities in cm/s (lower) for the 26.0 kg/m^3 density surface. Contour interval is 0.02 J/kg (upper) and the magnitude of flow is given by the arrow shown in the upper right corner (lower).

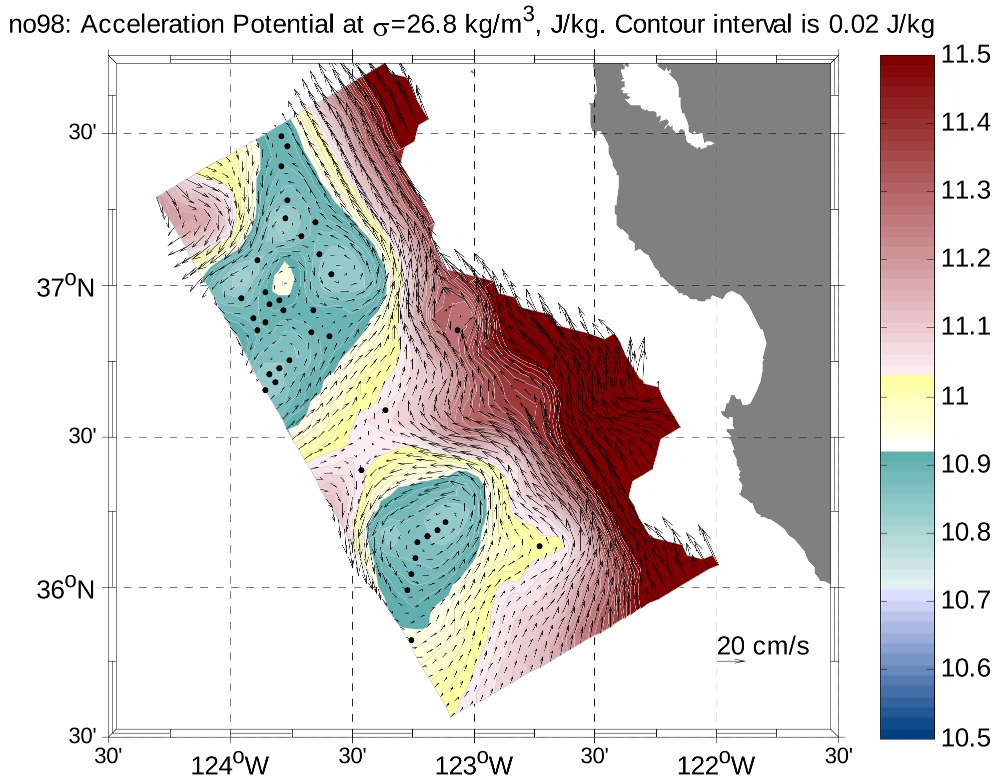


Figure 39. Acceleration potential in J/kg during November 1998 on the 26.8 kg/m^3 density surface. Contour interval is 0.02 J/kg.998. 26.8 kg/m^3 isopycnal, contour interval is 0.02 J/kg

5. Sea Surface Height – Geopotential and SSHA

On the geopotential (dynamic height) display in Figure 40 (upper), the isolines were oriented parallel to the coast through the center of the survey area. The minimum dynamic height of ~12.6 J/kg occurs along the eastern edge of the survey area north of 37°N and below 36°15´N. Geopotential increases from the north to the south and southeast, where maximum dynamic heights of ~14 J/kg and ~13.2 J/kg occurred, respectively. There are eddy-like features centered around these offshore maximums at 36°15´N, 123°17´W and at 36°37´N, 122°18´W. The surface geostrophic flow (0/1000 dbar) was equatorward except for the mesoscale cyclonic circulations previously noted.

The mean sea level anomaly shown on Figure 40 (lower) (4 November 1998) showed a range from a low of -4 cm near Pt. Reyes to a maximum of 7 cm near the southern vertex of the survey. This range compared favorably to the 1.1 J/kg range of dynamic height. Minor differences with the dynamic height field occurred principally along the coast where features in the altimeter field were shifted about 30–40 km to the north of their location on the geopotential field (Figure 40, upper).

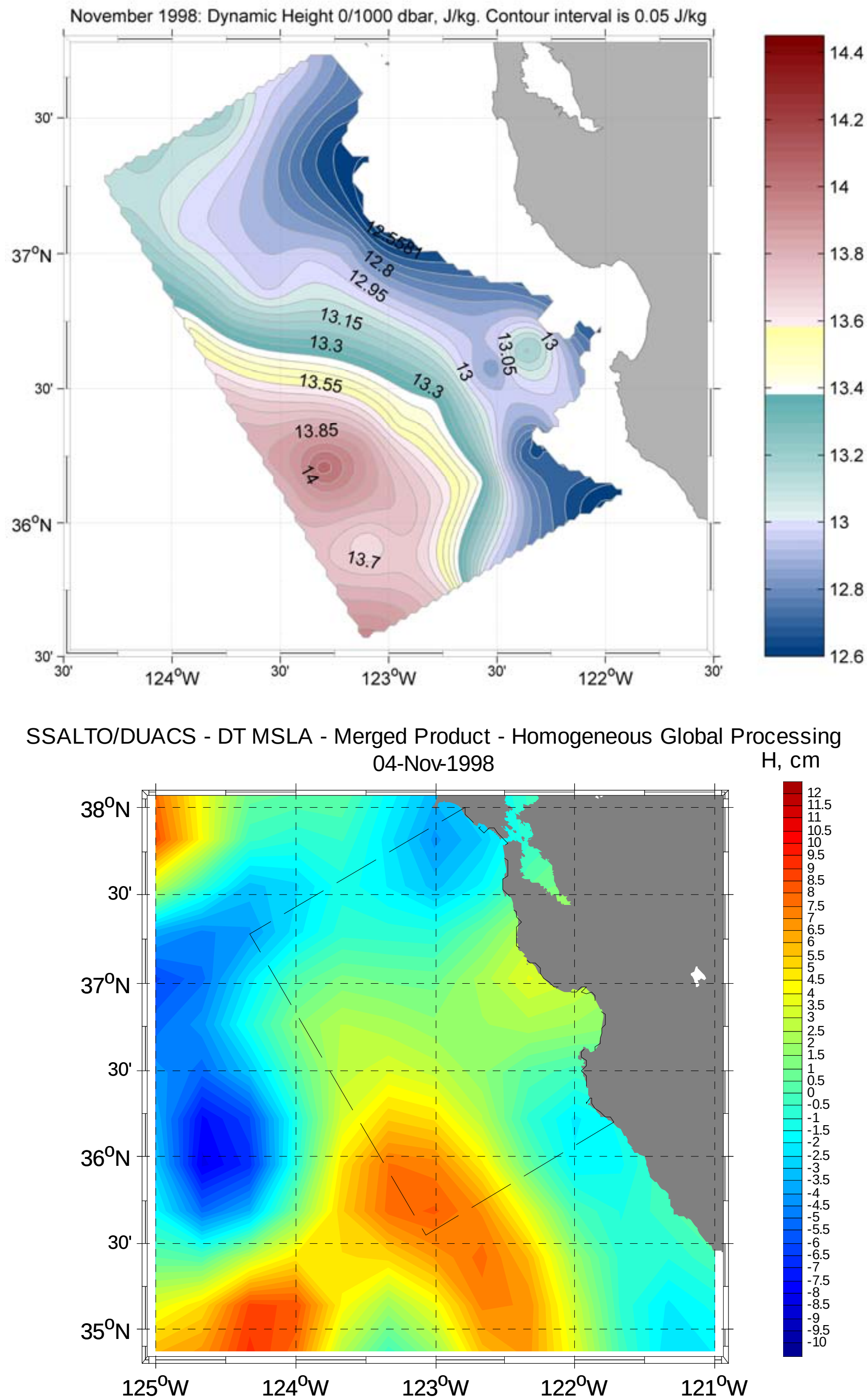


Figure 40. Geopotential (Dynamic Height) in J/kg for May 1998 from 0–1000 dbar (upper) and SSHA in cm (daily mean from 08 May). Contour interval is 0.05 J/kg. (upper) and 0.5 cm (lower).

E. JANUARY 1999

This survey was done by *R/V Point Sur*, which departed Moss Landing at 1646Z, 6 January. CTD observations began at 1010Z, 7 January at 37°16.69′N, 124°19.78′W and a chart of CTD station positions is shown in Figure 41. Three 24-hour time series were conducted, with the first beginning at 0727Z, 8 January, at 37°47.22′N, 123°14.56′W, in depth of 112 m. The second time series began off Point Reyes at 1004Z, 9 January at 37°34.24′N, 122°56.91′W, in depth of 117 m. The final time series began at 0330Z, 12 January, at 37°17.62′N, 122°39.21′W at 88 m. The vessel temporarily returned to Moss Landing at 1914Z, 13 January, and got back underway at 15002Z, 14 January, commencing CTD observations at 1628Z. CTD observations concluded at 1737Z, 19 January.

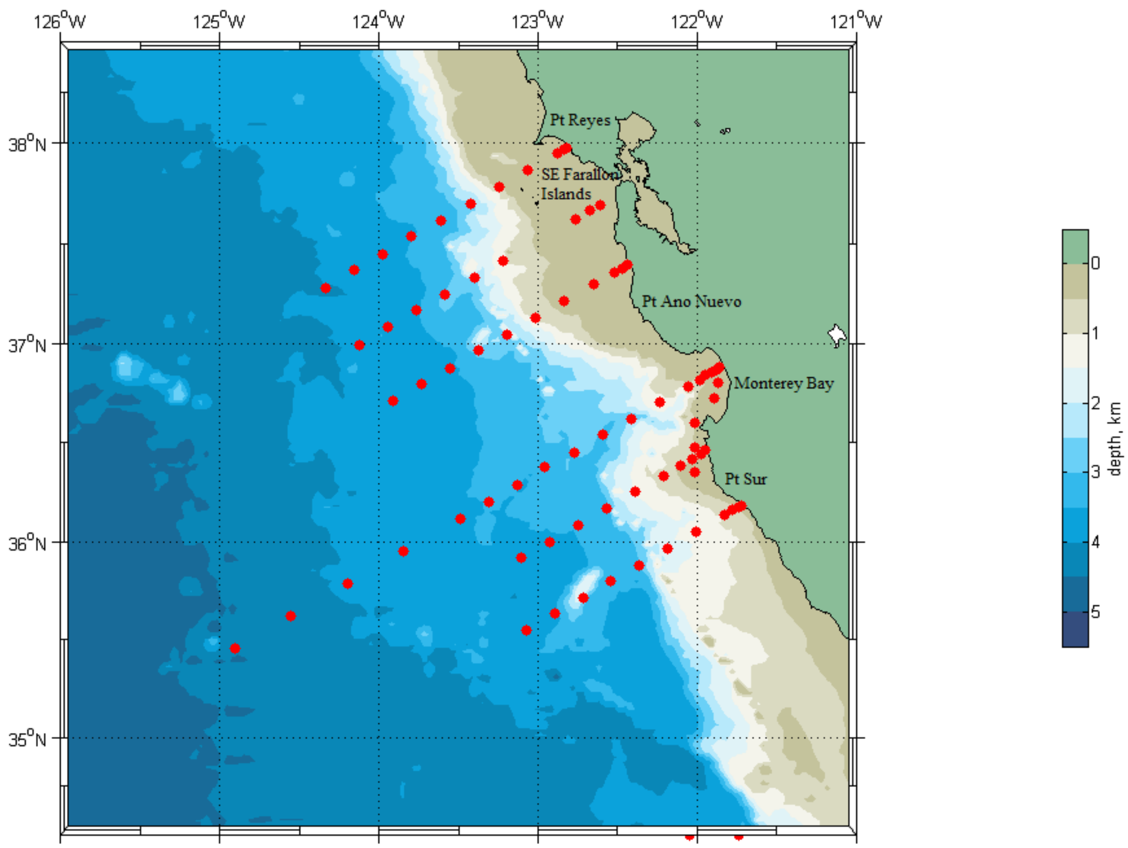


Figure 41. Station positions for January 1999 (shown by red dots).

1. T/S Diagram

The range of spiciness and associated water properties observed for the January 1999 cruise is shown by the black dots in Figure 40. Spiciness (potential temperature, salinity) ranged from approximately -0.05 kg/m^3 (9.3°C, 33.58) to 0.25 kg/m^3 (10.3°C, 33.85) on the 26.0 kg/m^3 density surface. For the deeper 26.8 kg/m^3 density surface, spiciness (potential temperature, salinity) ranged from -0.25 kg/m^3 (6.2°C, 34.00) to 0.00 kg/m^3 (6.8°C, 34.15). Sea surface temperatures ranged from 12°C–13°C and surface salinities from 32.6 to 33.6. Salinities between 4°C and 8°C were 0.1 less than mean values for the ten cruises.

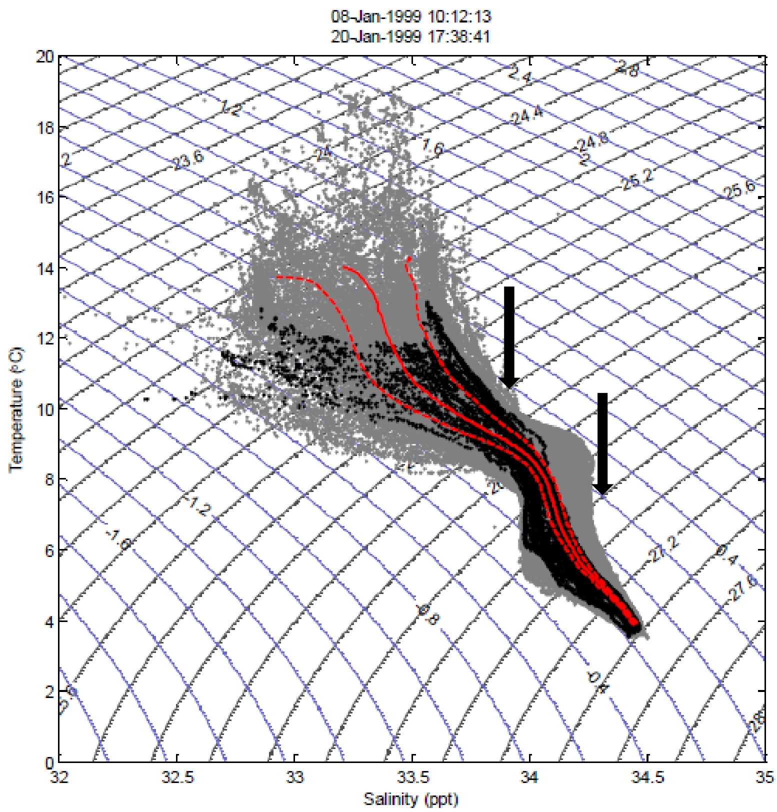
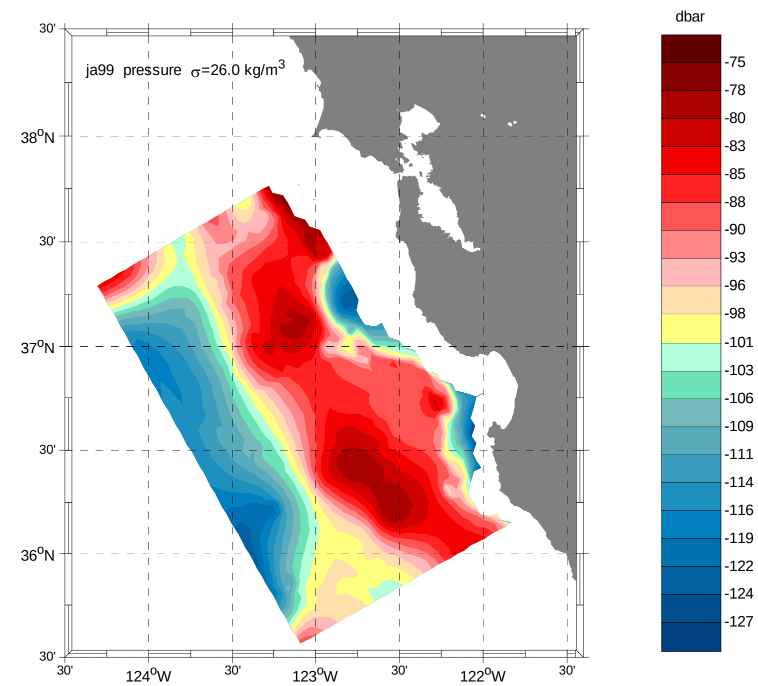


Figure 42. T/S Diagram for January 1999. . Black dots are data from the January 1999 cruise, and grey dots represent data from all 10 NAVO cruises. The solid (dashed) red line is the mean (± one standard deviation) of salinity as a function of potential temperature for all 10 NAVO cruises. Density anomalies are shown on the curved lines that slope upward to the right and spiciness is shown by the curved lines that slope downward to the right. Black arrows designate 26.0 and 26.8 kg/m^3 density surfaces.

2. Pressure

Figure 43 (upper) shows pressure of the 26.0 kg/m^3 isopycnal. Pressure levels ~100 dbar existed in a continuous northwest to southeast direction throughout the entire survey area. To the west of this, pressure levels decreased, reaching a minimum of approximately 127 dbar at multiple locations along the western boundary. There was a steep gradient of increased pressure levels occurs approaching the coast between 36°07°N and 36°22´N. To the east of 100 dbar, a pressure ridge occurred with minimum pressure less than 85 dbar. The pressure ridge was next to the coast in the area of the Farallon Islands but tended southwest along 123°W to the latitude of Point Sur, where it turned southeast off Pt. Año Nuevo and Monterey Bay, reaching pressure levels (125 dbar) similar to those found offshore along the western edge of the survey.

On the 26.8 kg/m^3 isopycnal (Figure 43, lower) pressure ranged between 340 and 377 dbar over much of the survey area. The shallowest pressures were centered near 36°00´N, 122°-35´W, where pressure ranged between 340 and 348 dbar. The area of lower overall pressures separates two southern regions of higher pressure (ranging between 386-423 dbar) which lie in a northeast to southwest direction, one offshore of the Monterey Bay, and Pt. Sur, the other along the western edge of the survey region



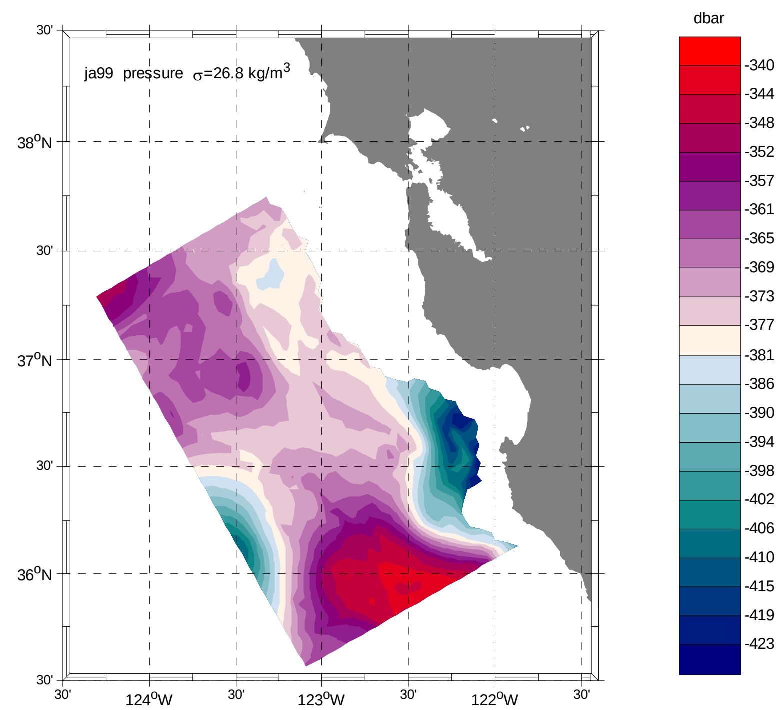
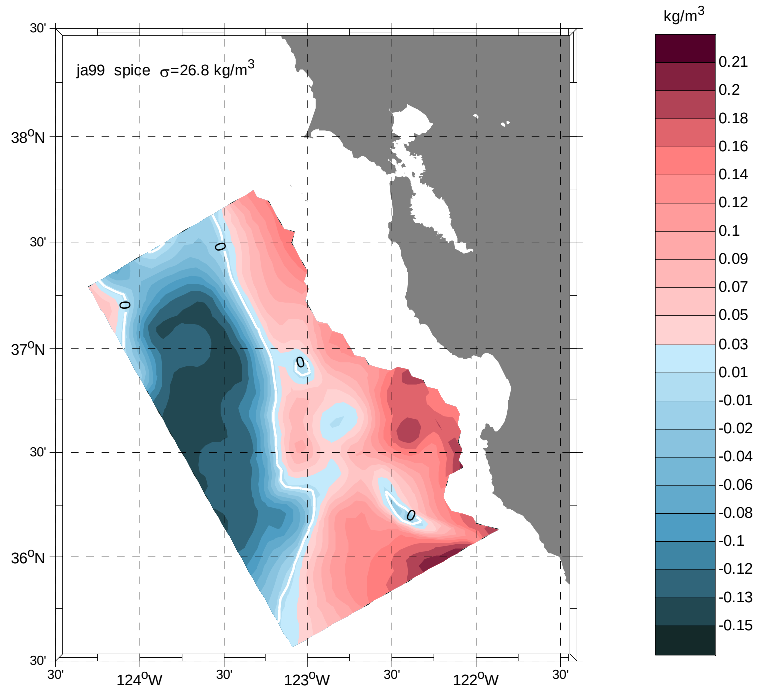


Figure 43. Pressure in dbar during January 1999 for the 26.0 kg/m^3 (upper) and 26.8 kg/m^3 density surfaces (lower). Contour interval is 2.6 dbar (upper) and 4.15 dbar (lower).

3. Spiciness

Although the 123°12´W meridian (spiciness 0.2 kg/m^3) roughly divides lower spiciness offshore waters from higher spiciness nearshore waters on the 26.0 kg/m^3 isopycnal (Figure 44, upper), mesoscale patches of high (low) spiciness were observed offshore (nearshore). The largest gradient of spiciness occurred along latitude 37°30´N, where spiciness ranged between 0.26 and 0.03 kg/m^3 between 123°00´W and 123°28´W.

On the 26.8 kg/m^3 isopycnal, the zero spiciness contour was oriented in a north-south direction through the survey area between 123°W to 123°30´W. The zero contour separated predominately positive spiciness levels to the east from negative spiciness to the west. Three small submesoscale intrusions of zero spiciness were observed within the higher spiciness inshore waters.



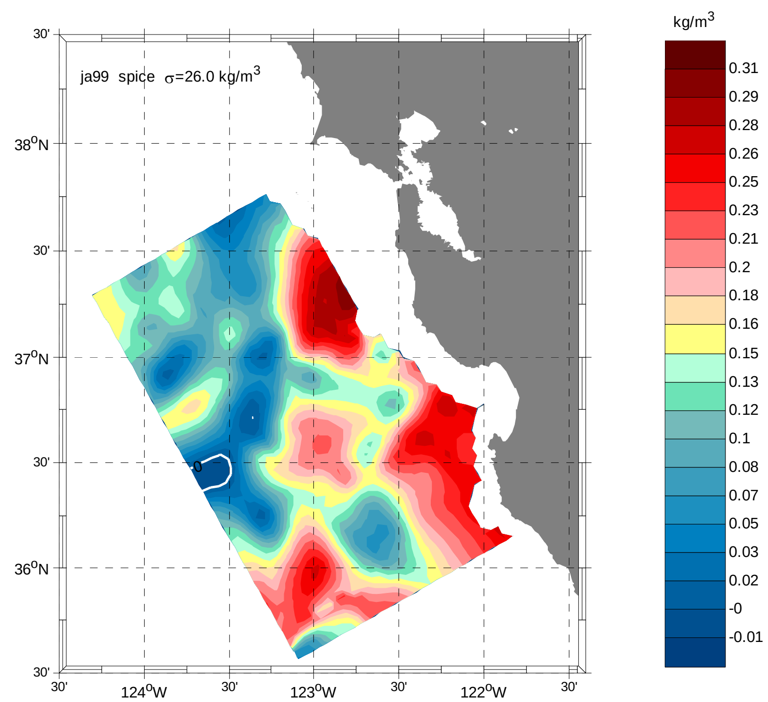
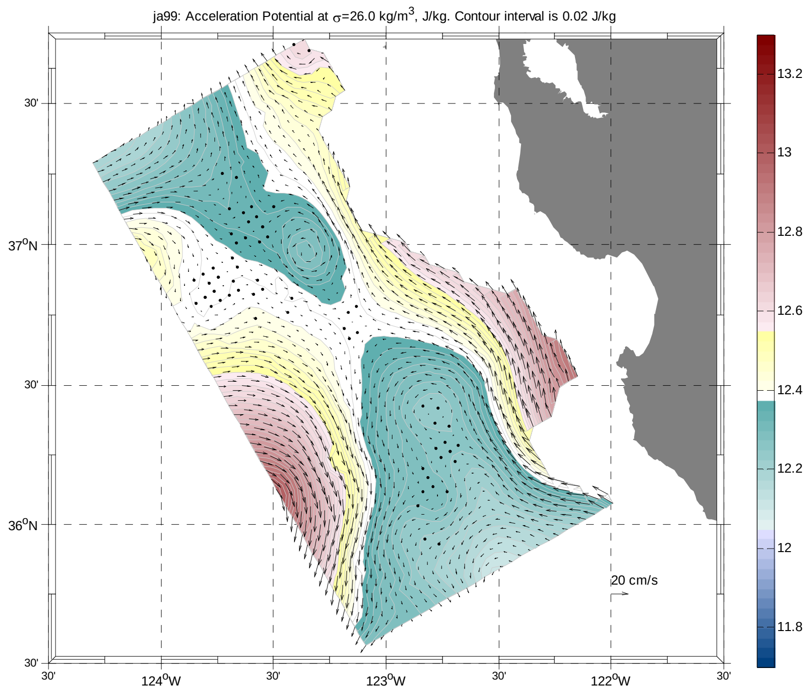


Figure 44. Spiciness in kg/m^3 during January 1999 for the 26.0 kg/m^3 (upper) and 26.8 kg/m^3 (lower) density surfaces. Contour interval is 0.018 kg/m^3 (upper) and 0.016 kg/m^3 (lower). White denotes the zero spiciness contour.

4. Acceleration Potential and ADCP

Acceleration potential on the 26.0 kg/m^3 isopycnal for the January 1999 survey (Figure 43, upper) most resembled the mean (Figure 8, upper). A ridge connected a region of maximum acceleration potential, 12.9 J/kg, on the offshore edge of the survey at 36°06′N to a region with similar dynamic height at the entrance to Monterey Bay. From the north and the south, troughs of low acceleration potential extend toward the ridge, separated by a distance of about 20 km at 36°40′N, 123°06′W, one centered at 36°58′N, 123°15′W and a second, larger feature centered at 36°22′N, 122°45′W. The general pattern of flow was poleward inshore, equatorward offshore, with flow directed inshore north of the ridge and onshore to the south of the ridge.

ADCP data on the 26.0 kg/m^3 isopycnal indicated variable flow in the northwest portion of the survey area. (Figure 45, lower). There was also cyclonic flow similar to that seen on the acceleration potential figure near 36°05′N, 122°58′W, though it occurred over a broader region in the acceleration potential figure.



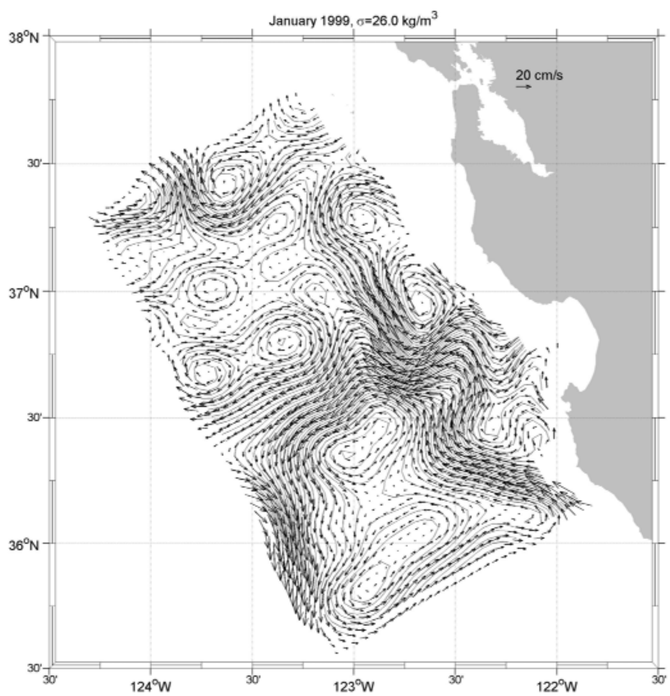


Figure 45. Acceleration potential in J/kg during January 1999 (upper) and ADCP velocities in cm/s (lower) for the 26.0 kg/m^3 density surface. Contour interval is 0.02 J/kg (upper) and the magnitude of flow is given by the arrow shown in the upper right corner (lower).

For acceleration potential on the 26.8 kg/m^3 surface (Figure 46), two locations of cyclonic flow are distinguishable in the western sections of the survey area. The larger of the two was located in the vicinity of 37°00′N, 123°27′W, while a smaller scale flow was located in the vicinity of 36°07′N, 123°27′W. Strong poleward flow was visible throughout much of the eastern portion of the survey area, evidence of a strong undercurrent and/or inshore countercurrent.

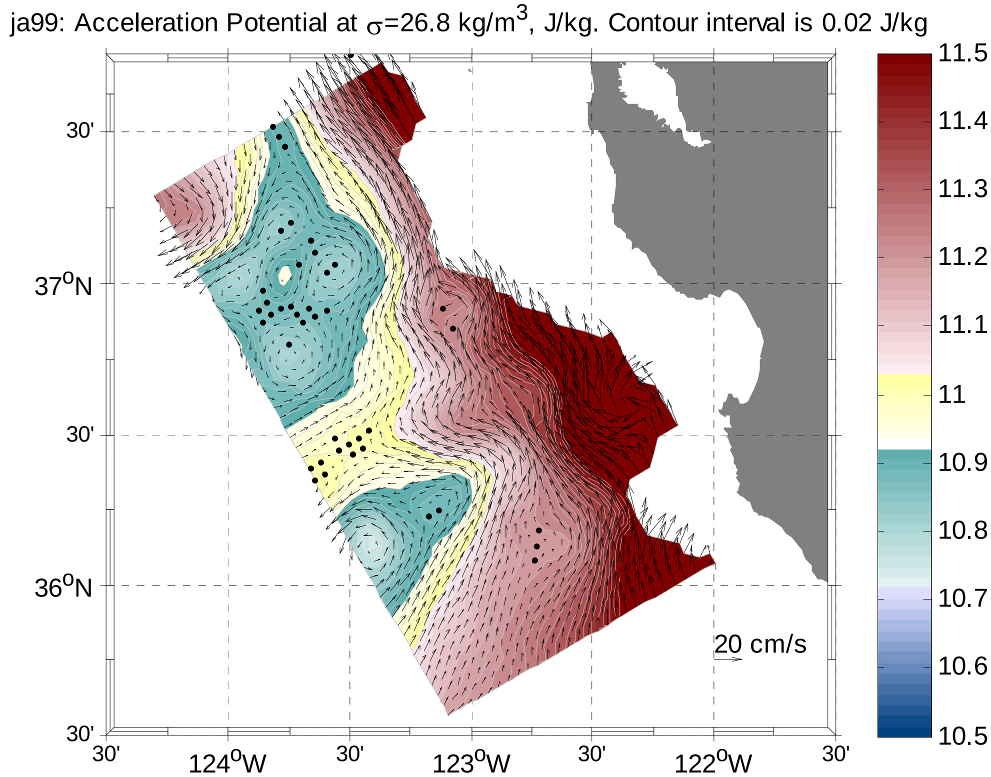


Figure 46. Acceleration potential in J/kg during January 1999 on the 26.8 kg/m^3 density surface. Contour interval is 0.02 J/kg.

5. Sea Surface Height – Geopotential and SSHA

Figure 47 (upper) shows the distribution of geopotential (dynamic height) for the January 1999 survey. The isosteres were oriented parallel to the coast near the western and eastern boundaries of the survey area. The largest magnitude of geopotential (~13.7 J/kg) occurred on the western boundary between 36°N and 36°30′N. Geopotential decreased moving inshore (signifying equatorward flow) until a trough in geopotential was encountered about halfway to the western edge of the survey. To the east of this trough, geopotential increased and geostrophic flow (referenced to 1000 dbar) was poleward. On the northern boundary near 37°N, a maximum of geopotential, 13.25 J/kg, occurred, suggesting westward flow in this part of the survey area,

As for the 1998 surveys, the chart of MSLA for January 13, 1999 (Figure 47, lower), agrees well with the pattern of geopotential (referenced to 1000 dbar) observed by the ship. MSLA ranged from -10 to -2 cm compared to a range of -13.7 to -12.6 cm for steric height referenced to 1000 dbar. Note too how the pattern of minimum MSLA follows the path of the trough in dynamic height observed (Figure 47, upper).

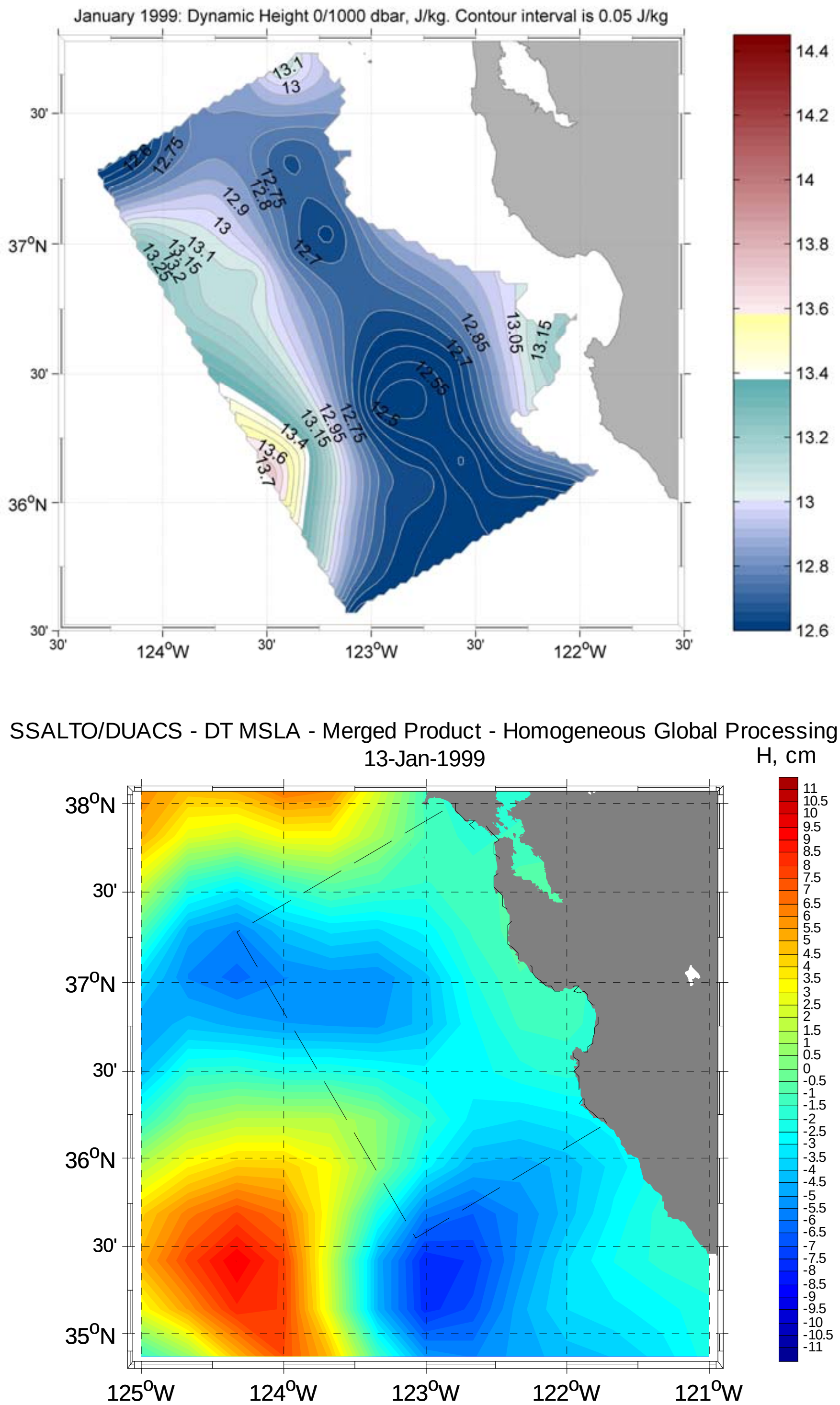


Figure 47. Geopotential (Dynamic Height) in J/kg for January 1999 from 0–1000 dbar (upper) and SSHA in cm (daily mean from 08 May). Contour interval is 0.05 J/kg. (upper) and 0.5 cm (lower).

F. NOVEMBER 1999

This survey was done by *R/V Point Sur*, which departed Moss Landing at 1636Z, 9 November. CTD observations began at 0657Z, 10 November, at 37°16.78´N, 124°19.92´W, and a chart of CTD station positions is shown in Figure 48. Three 24-hour time series were conducted, with the first beginning at 0355Z, 11 November, at 37°47.24´N, 123°14.65´W, in depth of 110.6 m. The second time series began at 0642Z, 12 November, at 37°32.17´N, 122°56.83´W in depth 113 m. The final time series began at 1740Z, 14 November, at 37°17.64´N, 122°39.21´W, in depth of 91.6 m. CTD observations for the first leg of the cruise ended at 2357Z, 15 November, and the *Point Sur* arrived at Moss Landing at 0044Z, 16 November.

The survey resumed with *Point Sur* getting underway from at 1631Z, 16 November. CTD observations began at 1826Z, 16 November, at 36°47.78´N, 121°50.79´W. CTD observations concluded at 2243Z, 22 November.

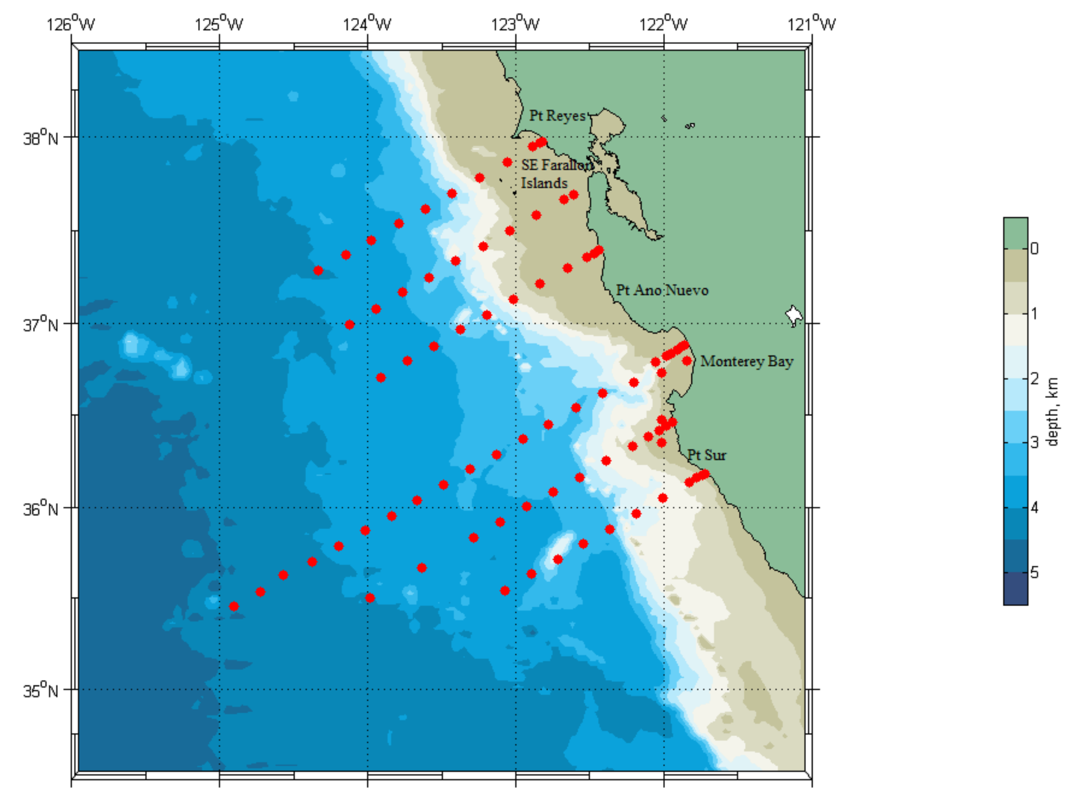


Figure 48. Station positions for November 1999 (shown by red dots).

1. T/S Diagram

The range of spiciness and associated water properties observed for the November 1999 cruise is shown by the black dots in Figure 49. Spiciness (potential temperature, salinity) ranged from approximately -0.29 kg/m^3 (8.8°C, 33.50) to 0.25 kg/m^3 (10.3°C, 33.80) on the 26.0 kg/m^3 density surface. For the deeper 26.8 kg/m^3 density surface, spiciness (potential temperature, salinity) ranged from -0.35 kg/m^3 (5.4°C, 33.95) to 0.00 kg/m^3 (6.8°C, 34.20). Sea surface temperatures ranged from 14°C–15°C and sea surface salinity ranged from 33–33.6. For waters between 4.5°C–8.5°C, salinities were amongst the lowest observed for these ten cruises.

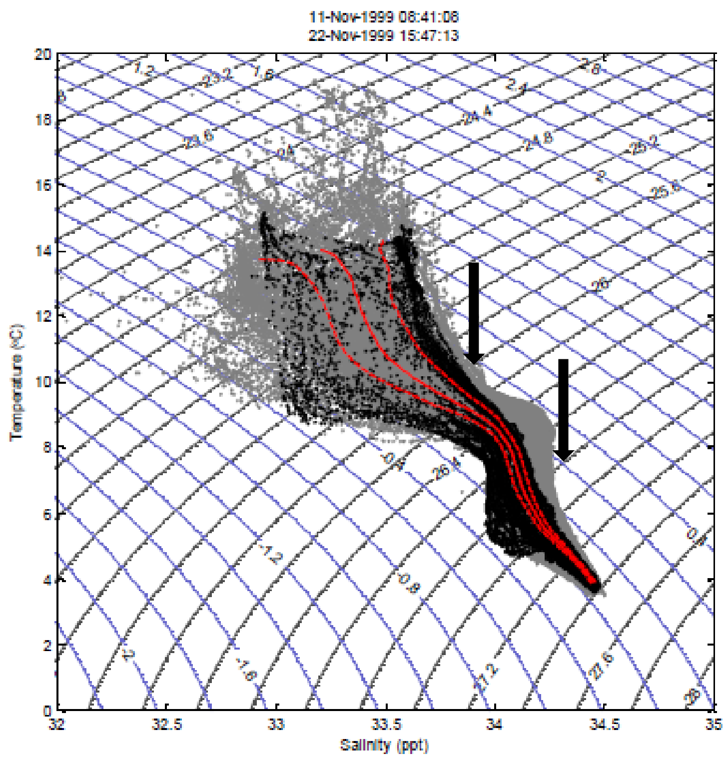


Figure 49. T/S Diagram for November 1999. . Black dots are data from the November 1999 cruise, and grey dots represent data from all 10 NAVO cruises. The solid (dashed) red line is the mean (± one standard deviation) of salinity as a function of potential temperature for all 10 NAVO cruises. Density anomalies are shown on the curved lines that slope upward to the right and spiciness is shown by the curved lines that slope downward to the right. Black arrows designate 26.0 and 26.8 kg/m^3 density surfaces.

2. Pressure

Figure 50 shows pressure on both the 26.0 kg/m^3 (upper) and 26.8 kg/m^3 (lower) surfaces. Pressure variability in the alongshore direction exceeded that of onshore variability for both isopycnals. For 26.0 kg/m^3 minimum pressure was approximately 72 dbar in the southwest part of the survey area, centered near 36°00´N, 122°52´W. Pressures throughout the southeast part of the survey were less than 98 dbar with the exception of higher pressure levels (between 98 to 120 dbar) intruding from the southeast corner of the survey area. The 26.0 kg/m^3 isopycnal was depressed to higher pressure levels to the northwest, with pressure maximums of around 130 dbar. For the northernmost portion of the survey area, the 26.0 kg/m^3 isopycnal was elevated to lower pressures, 80 to 90 dbar.

For the 26.8 kg/m^3 isopycnal, lower pressure was seen in the northwest part of the survey area, with the pressure minimum approximately 340 dbar centered at 37°15´N, 123°45´W. From here, pressure increased (deepening of isopycnal) to the southeast through the survey area where pressures ranged between 381 and 406 dbar. In the southernmost area of the survey, the 26.8 kg/m^3 isopycnal shoaled, with pressure decreasing to approximately 357 dbar.

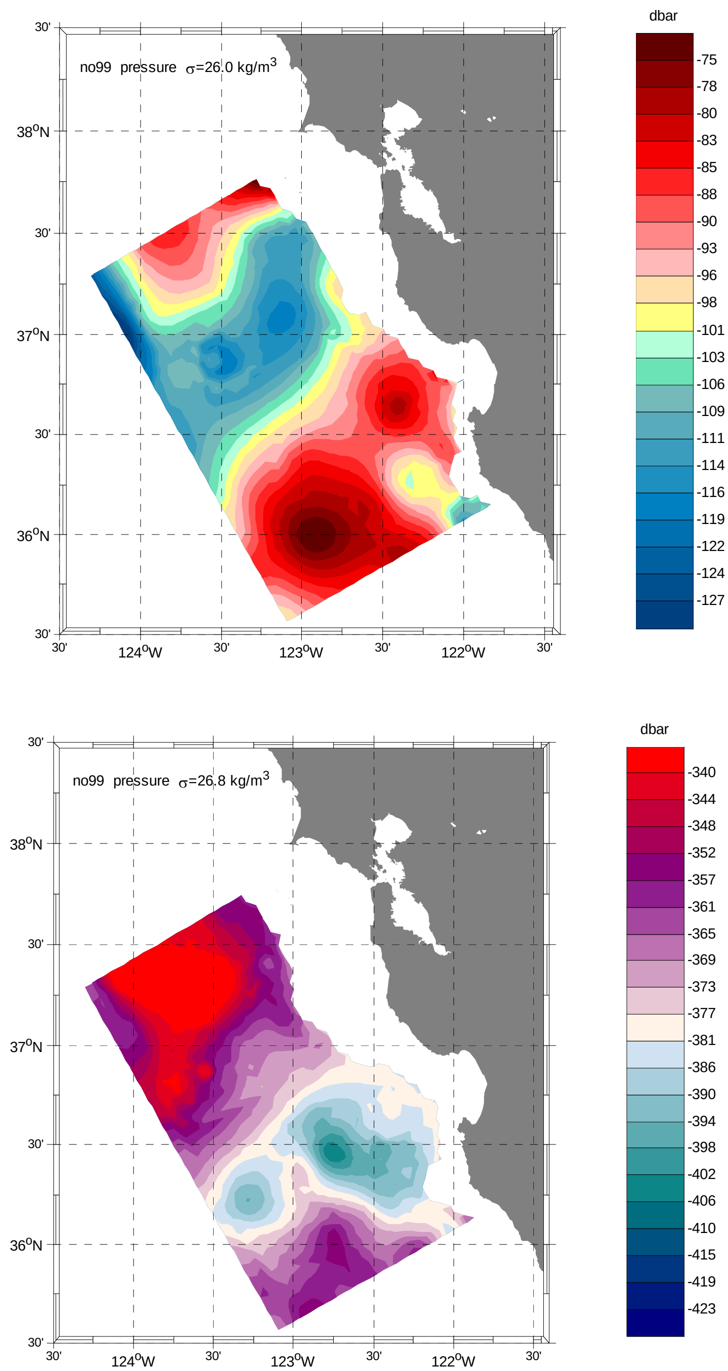


Figure 50. Pressure in dbar during November 1999 for the 26.0 kg/m^3 (upper) and 26.8 kg/m^3 density surfaces (lower). Contour interval is 2.6 dbar (upper) and 4.15 dbar (lower).

3. Spiciness

Spiciness on the 26.0 kg/m^3 isopycnal (Figure 51, upper) decreased in magnitude moving away from the coast where a maximum of approximately 0.29 kg/m^3 was seen centered at 37°15′N, 122°51′W. The 0.2 kg/m^3 spiciness contour separated offshore (lower spiciness) from onshore (higher spiciness) waters and laid along 123°12′W except south of 36°24′W where it was located 50 km offshore. There were two isolated locations along the western boundary of the survey where spiciness decreased to less than or equal to zero in the vicinity of 36°54′N, 123°51′W and 36°54′N, 123°37′W.

On the 26.8 kg/m^3 isopycnal (Figure 51, lower), the zero spiciness contour was between 123°W and 123°30′W except at the northern boundary of the survey where it changed orientation and moved offshore. So, negative spiciness was predominant to the west, while positive spiciness was found through much of the eastern portion. Maximum spiciness occurred near to the shore.

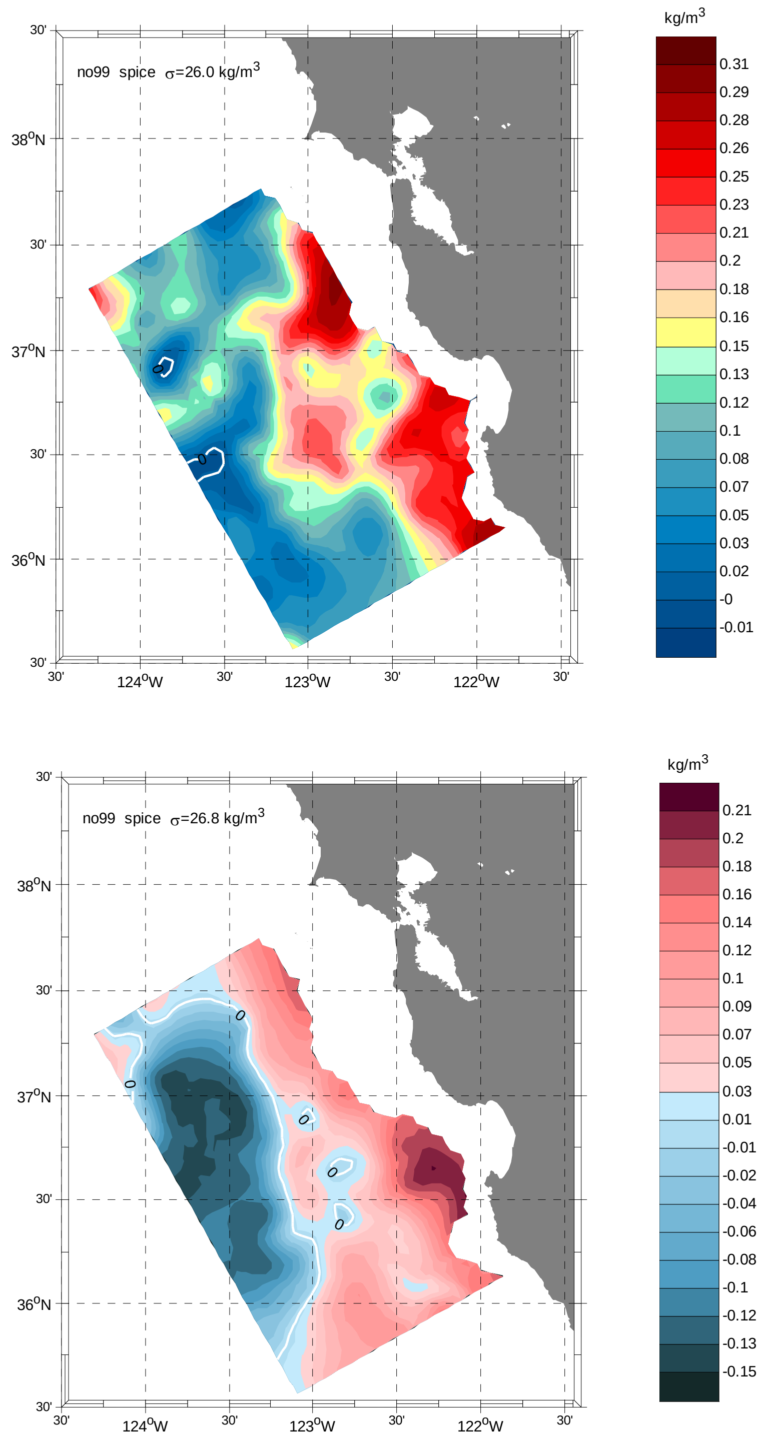


Figure 51. Spiciness in kg/m^3 during November 1999 for the 26.0 kg/m^3 (upper) and 26.8 kg/m^3 (lower) density surfaces. Contour interval is 0.016 kg/m^3 (upper) and 0.018 (lower). White denotes zero spiciness contour.

4. Acceleration Potential and ADCP

Figure 52 (upper) displays acceleration potential on the 26.0 kg/m^3 for the November 1999 survey. Maximum acceleration potential of 12.7 J/kg, corresponding to anticyclonic flow, was centered at 36°30´N, 122°45´W. Minimum acceleration potential, 11.9 J/kg, was located on the northern survey boundary at 124°00´W. Poleward flow, entering the southern survey area at the coast, circulated westward around the maximum and thence northward between 123°00´W to 123°30´W. Southward flow was strongest along 124°00´W.

ADCP measurements on the 26.0 kg/m^3 isopycnal are shown in Figure 52 (lower). An anti-cyclonic flow feature was centered around 36°52´N, 123°48´W, similar to that seen on the display of acceleration potential (with the exception that the acceleration potential feature is not surrounded by a large cyclonic flow). There was an appearance of anti-cyclonic flow in the northeast part of the survey area centered around 37-28°N, 123-28°W, where flow was distinctly poleward in the same region on the acceleration potential figure. Flow opposite to the poleward flow seen in the acceleration potential figure also occurred in the vicinity of 35°45´N, 122°30´W.

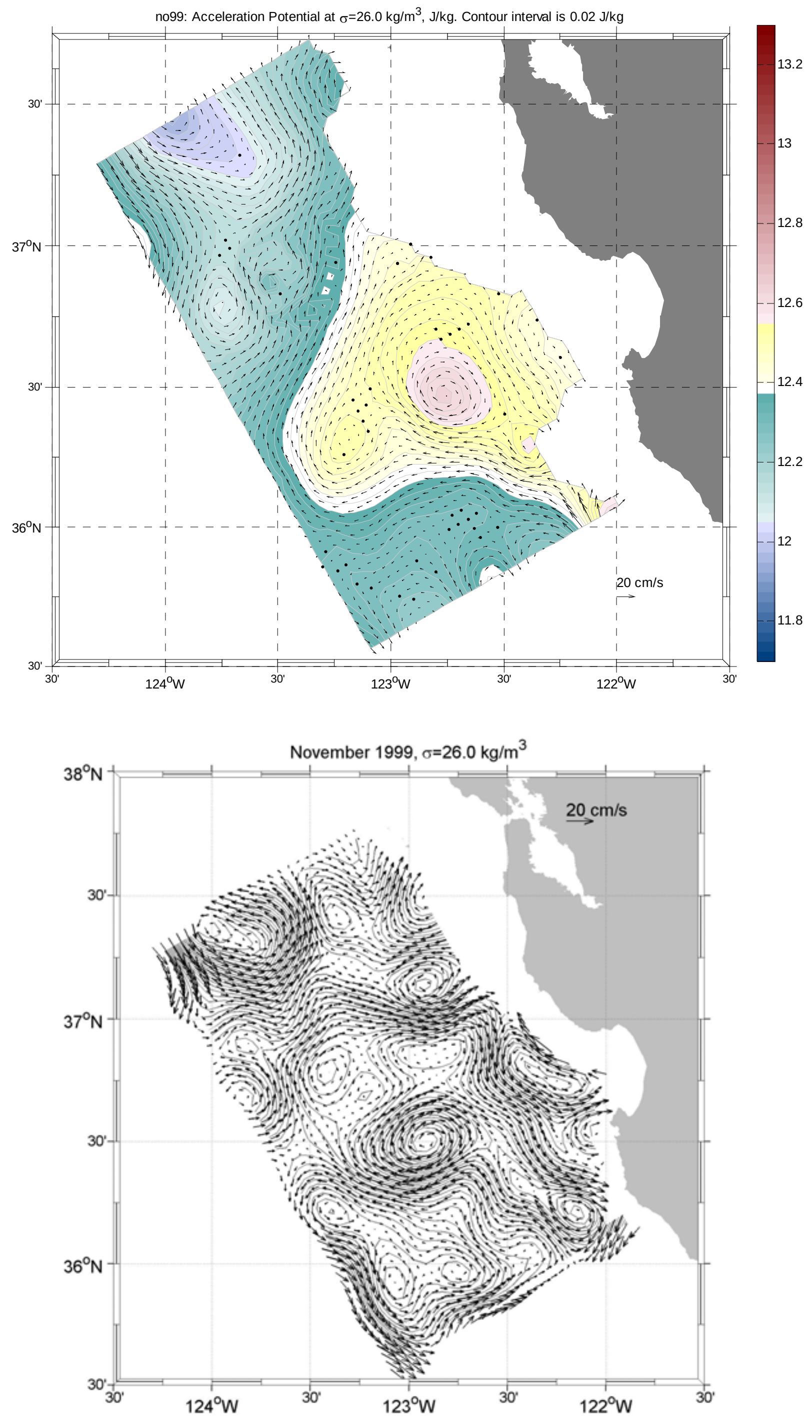


Figure 52. Acceleration potential in J/kg during November 1999 (upper) and ADCP velocities in cm/s (lower) for the 26.0 kg/m^3 density surface. Contour interval is 0.02 J/kg (upper) and the magnitude of flow is given by the arrow shown in the upper right corner (lower).

Figure 53 shows acceleration potential on the 26.8 kg/m^3 isopycnal. There was a large cyclonic feature centered at 36°48′N, 123°32′W. A second cyclonic flow feature was visible slightly to the southeast at 36°13′N, 123°14′W. A strong inshore countercurrent was visible through the entire eastern region of the survey area along the coast.

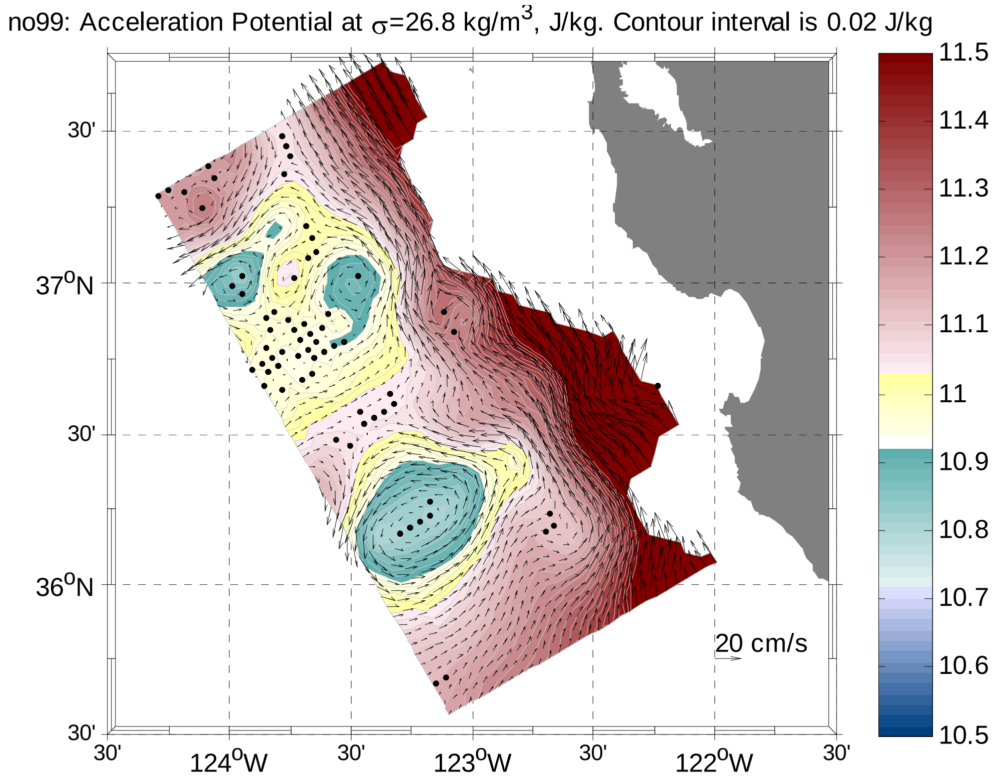


Figure 53. Acceleration potential in J/kg during November 1999 on the 26.8 kg/m^3 density surface. Contour interval is 0.02 J/kg

5. Sea Surface Height–Geopotential and SSHA

Figure 54 (upper) shows geopotential (dynamic height) at the sea surface relative to 1000 dbar. A trough of dynamic height extended along the coast at a distance of about 100 km from shore. At a distance of 50 km from the coast, a ridge (greater than 13.0 J/kg) in dynamic topography occurred. The largest magnitude of geopotential (~13.3 J/kg) occurred along the western boundary. The isolines shifted from parallel to the coast at the area of maximum geopotential to normal to the coast as the gradient decreased, evidence of a possible cyclonic recirculation of the offshore waters in the northern part of the survey area. Dynamic height decreased to less than 12.95 J/kg offshore Monterey Bay, evidence of equatorward geostrophic flow in this region.

Figure 54 (lower) shows MSLA for November 16, 1999. There is a positive MSLA in the northeast portion of the survey area, with a large region of greater than three centimeter sea level elevation. Directly west of this, MSLA decreased, with negative sea level anomalies, -3 to -6 centimeters. At the center of the survey region, there was a near zero anomaly; this decreased towards the southeast region of the survey to between -3 to -6 cm. The pattern if MSLA variability was similar to that for dynamic height. The range of MSLA was 9 cm, the same as that for dynamic height.

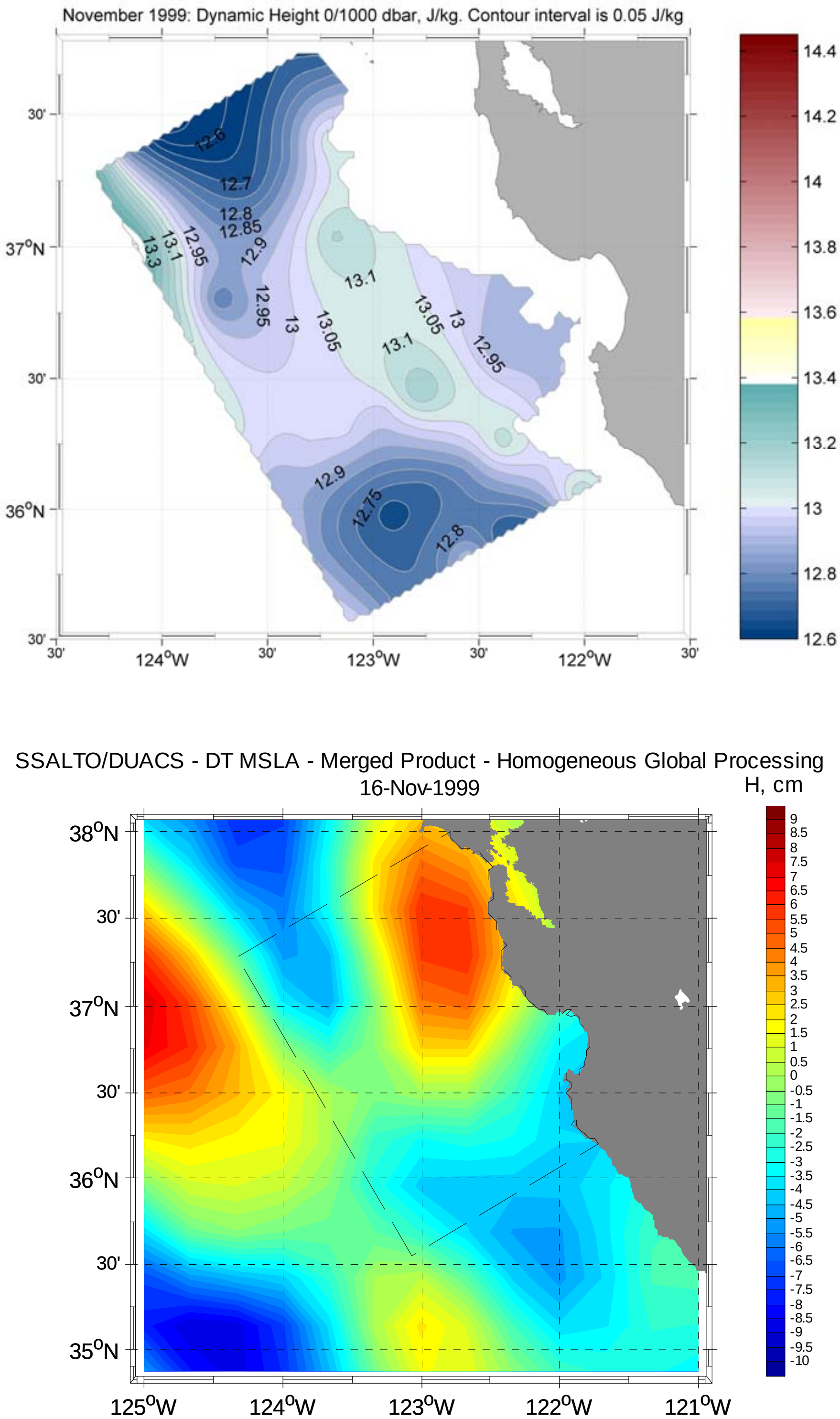


Figure 54. Geopotential (Dynamic Height) in J/kg for November 1999 from 0–1000 dbar (upper) and SSHA in cm (daily mean from 08 May). Contour interval is 0.05 J/kg. (upper) and 0.5 cm (lower)

G. SEPTEMBER 2000

This survey was done by *R/V New Horizon*, which departed Redwood City at 1941Z, 3 September. CTD observations (station positions shown in figure 55), and the first 24-hour time series, began at 0206Z, 4 September, at 37°32.16´N, 122°56.82´W in depth 108.8 m. The second time series began at 0555Z, 5 September, at 37°47.08´N, 122°57.03´W in depth 115 m. Following the second time series the *New Horizon* arrived at Hunters Point, San Francisco for mechanical repairs, with the survey resuming at 2152Z, 6 September. CTD observations along various CalCOFI lines continued from 0125Z, 7 September, to 0048Z, 12 September. A third time series began at 1329Z, 12 September, at 36°47.81´N, 121°50.74´W in depth 228 m. CTD observations along CalCOFI line 67 began at 1707Z, 13 September, and concluded at 1111Z, 16 September. The vessel arrived in San Diego at 1434Z, 18 September.

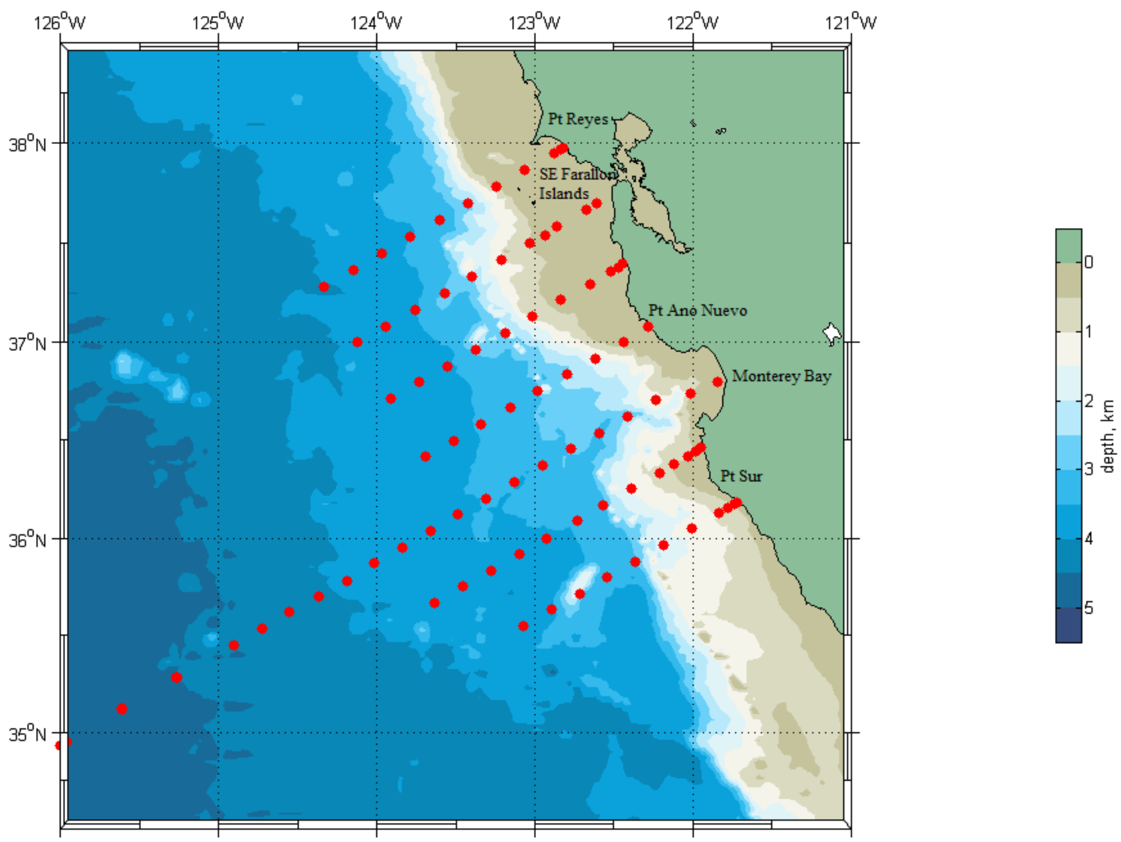


Figure 55. Station positions for September 2000 (shown by red dots).

1. T/S Diagram

The range of spiciness and associated water properties observed for the September 2000 cruise is shown by the black dots in Figure 49. Spiciness (potential temperature, salinity) ranged from approximately -0.10 kg/m^3 (9.3°C, 33.60) to 0.20 kg/m^3 (10.3°C, 33.80) on the 26.0 kg/m^3 density surface. For the deeper 26.8 kg/m^3 density surface, spiciness (potential temperature, salinity) ranged from -0.25 kg/m^3 (5.7°C, 34.00) to 0.05 kg/m^3 (7.0°C, 34.25). Sea surface temperatures ranged widely, 16°C-19°C, and sea surface salinities ranged from 33 to 33.5.

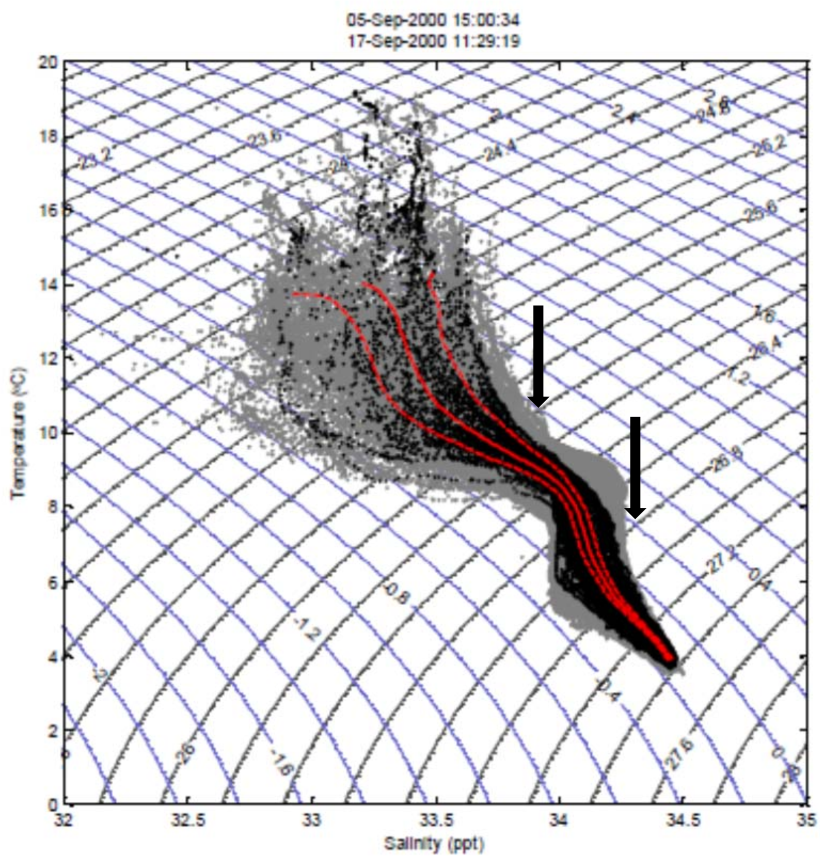


Figure 56. T/S Diagram for September 2000. . Black dots are data from the September 2000 cruise, and grey dots represent data from all 10 NAVO cruises. The solid (dashed) red line is the mean (± one standard deviation) of salinity as a function of potential temperature for all 10 NAVO cruises. Density anomalies are shown on the curved lines that slope upward to the right and spiciness is shown by the curved lines that slope downward to the right. Black arrows designate 26.0 and 26.8 kg/m^3 density surfaces.

2. Pressure

Pressure on the 26.0 kg/m^3 isopycnal indicated a region of lower pressure intersecting the middle and center of the survey area between 50 and 70 dbar (Figure 57, upper).. There were three areas where distinctly larger (deeper) pressure levels existed. These were in the northwest and southwest corners of the survey area as well as near to the coast in the vicinity of 36°33´N, 122°03´W. These deeper pressures ranged between 128 and 139 dbar.

On the 26.8 kg/m^3 isopycnal, a ridge of pressure levels was found on the western side of the survey area, centered around 36°33´N, 123°33´W. The pressure minimum here ranged between 322–327 dbar. North and east of this feature, pressure troughs increased to maximums of between 404-418 dbar. Along 36°N, the pressure ridge changed orientation to east-west.

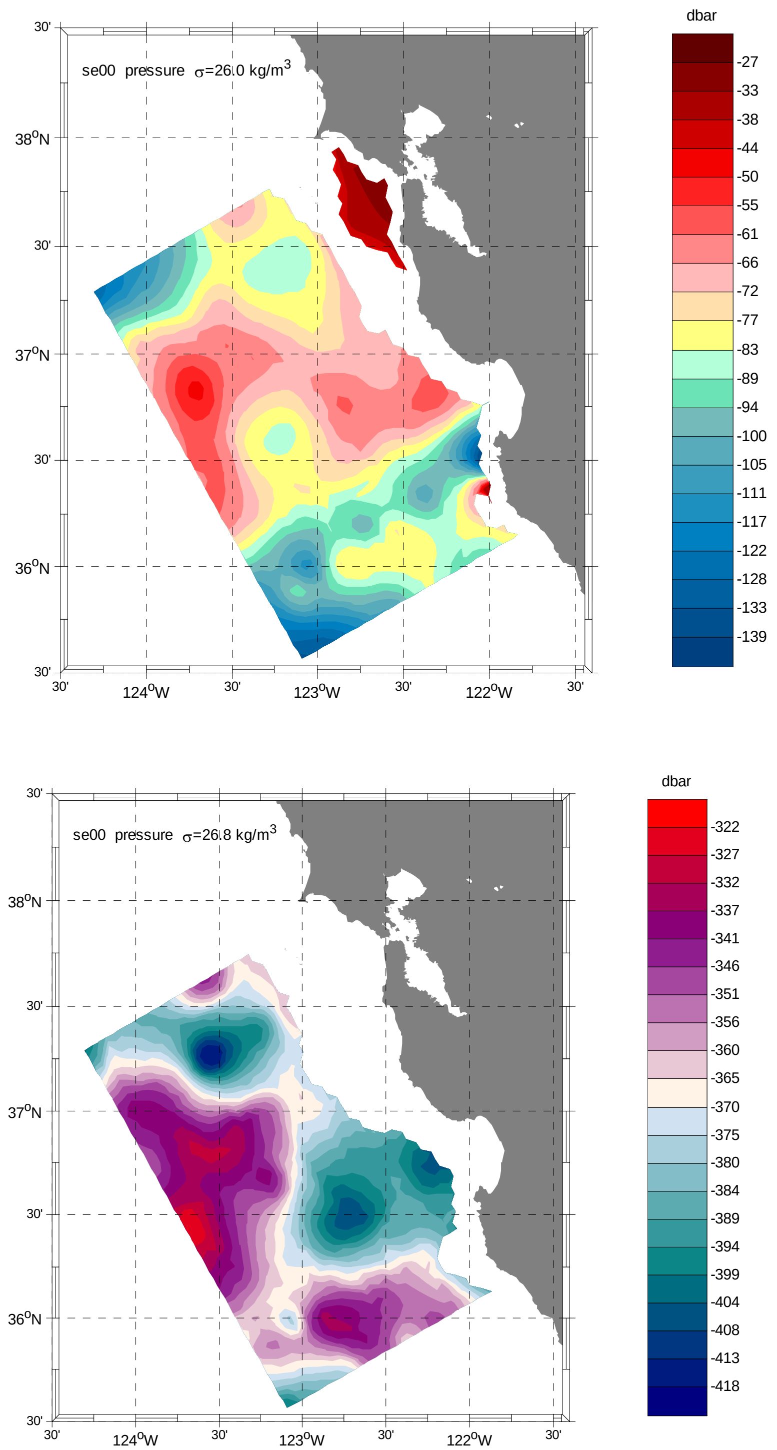
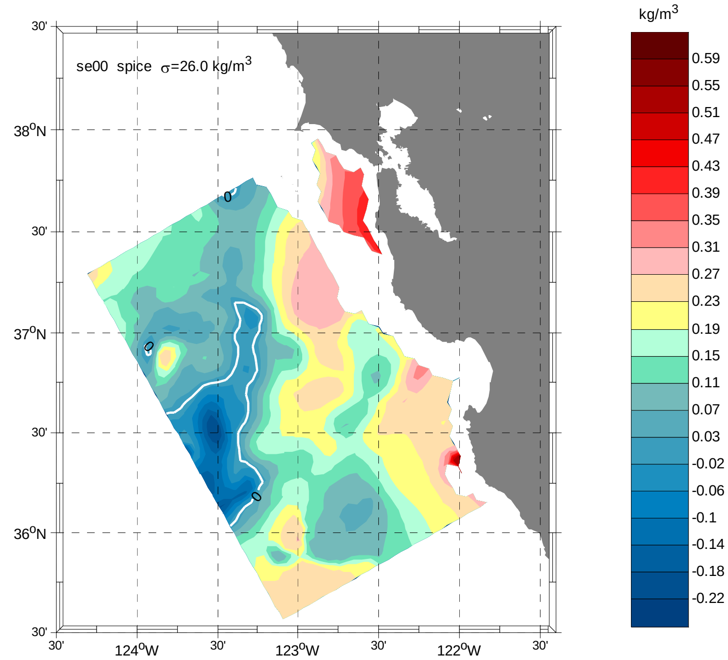


Figure 57. Pressure in dbar during September 2000 for the 26.0 kg/m^3 (upper) and 26.8 kg/m^3 density surfaces (lower). Contour interval is 5.6 dbar (upper) and 4.8 dbar (lower).

3. Spiciness

Spiciness, on the 26.0 kg/m^3 isopycnal was sporadic (Figure 58, upper). The most distinct feature was a region of negative spiciness that was centered around 36°30′N, 123°30′W in the western region of the survey area. Spiciness was predominately positive throughout the rest of the survey area, with a general increase approaching the coast. The 0.2 kg/m^3 spiciness contour lay along ~123°06′W at its western extreme but not near 36°24′N.

Spiciness on the 26.8 kg/m^3 isopycnal is shown in Figure 58 (lower). Negative spiciness levels in the west are separated from positive spiciness in the east by the zero spiciness contour which traveled in a north-south direction. There were some isolated locations of near zero spiciness that occurred in the eastern part of the survey area.



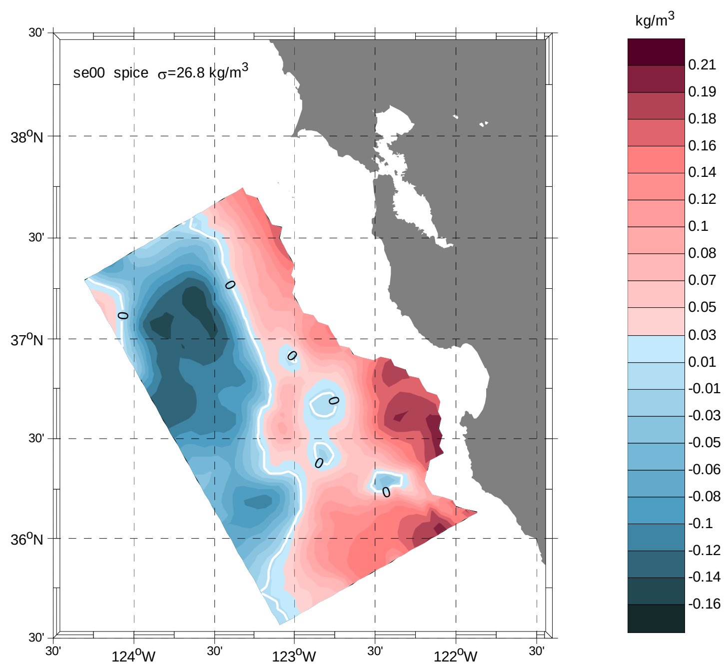
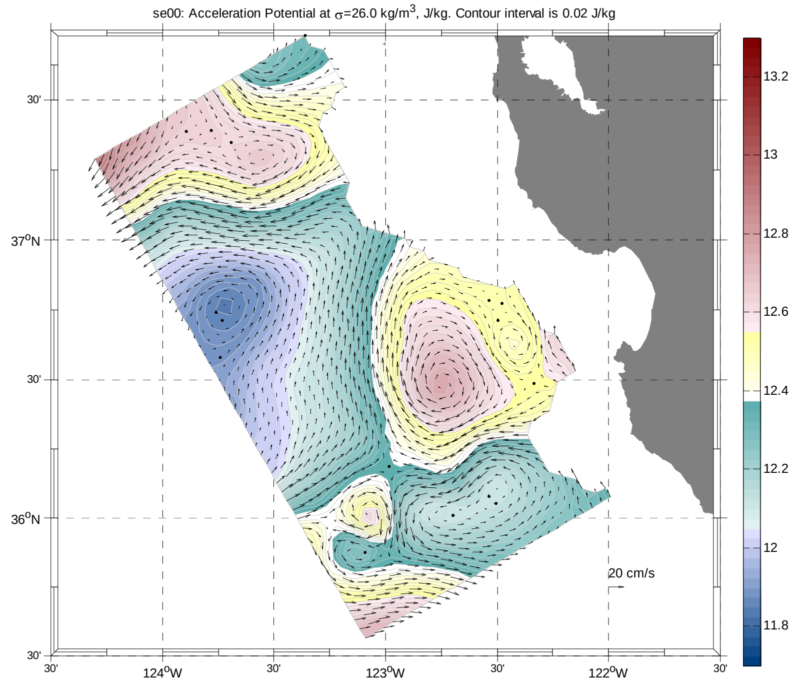


Figure 58. Spiciness in kg/m^3 during September 2000 for the 26.0 kg/m^3 (upper) and 26.8 kg/m^3 (lower) density surfaces. Contour interval is 0.041 kg/m^3 (upper) and 0.019 kg/m^3 (lower).White denotes zero spiciness contour.

4. Acceleration Potential and ADCP

Figure 59 (upper) shows acceleration potential on the 26.0 kg/m^3 surface for the September 2000 survey. Offshore Monterey Bay, a 100 km diameter region of anticyclonic flow was centered at 36°30´N, 122°45´W with maximum acceleration potential of 12.8 J/kg. Further offshore and slightly north at 36°45´N, 123°45´W, minimum acceleration potential, 11.9 J/kg was observed. These two features were separated by poleward flow along 123°00´W through the center of the survey area between 36–37°N. A ridge of acceleration potential was observed along 37°15´N with offshore flow to its south and onshore flow to the north, the latter toward Pt. Reyes. The southern region of the survey off Pt. Sur was marked by offshore flow to 123°00´W and a complex flow pattern further west associated with a series of sub-mesoscale cyclonic and anticyclonic features.

ADCP currents on the 26.0 kg/m^3 isopycnal showed similarities with acceleration potential. There was a similar appearance of an anticyclonic flow in the east and a smaller cyclonic flow in the west. Strong offshore flow was evident in the northwest, coinciding with the offshore flow seen in the southern part anticyclonic flow north of 37°N described above. Poleward flow along the coast turned westward at 37°20´N.



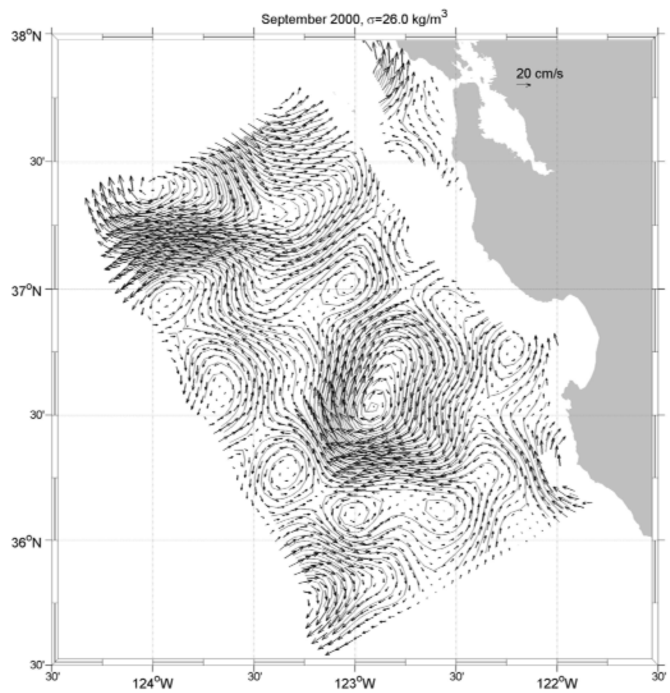


Figure 59. Acceleration potential in J/kg during September 2000 (upper) and ADCP velocities in cm/s (lower) for the 26.0 kg/m^3 density surface. Contour interval is 0.02 J/kg (upper) and the magnitude of flow is given by the arrow shown in the upper right corner (lower).

Acceleration potential on the 26.8 kg/m^3 isopycnal showed an anti-cyclonic feature in the northwest portion of the survey area, with a slightly weaker cyclonic feature directly to the east (Figure 60). Another distinct feature was a cyclonic flow centered around 36°16´N, 123°05´W. Strong poleward flow was visible throughout the eastern part of the survey area.

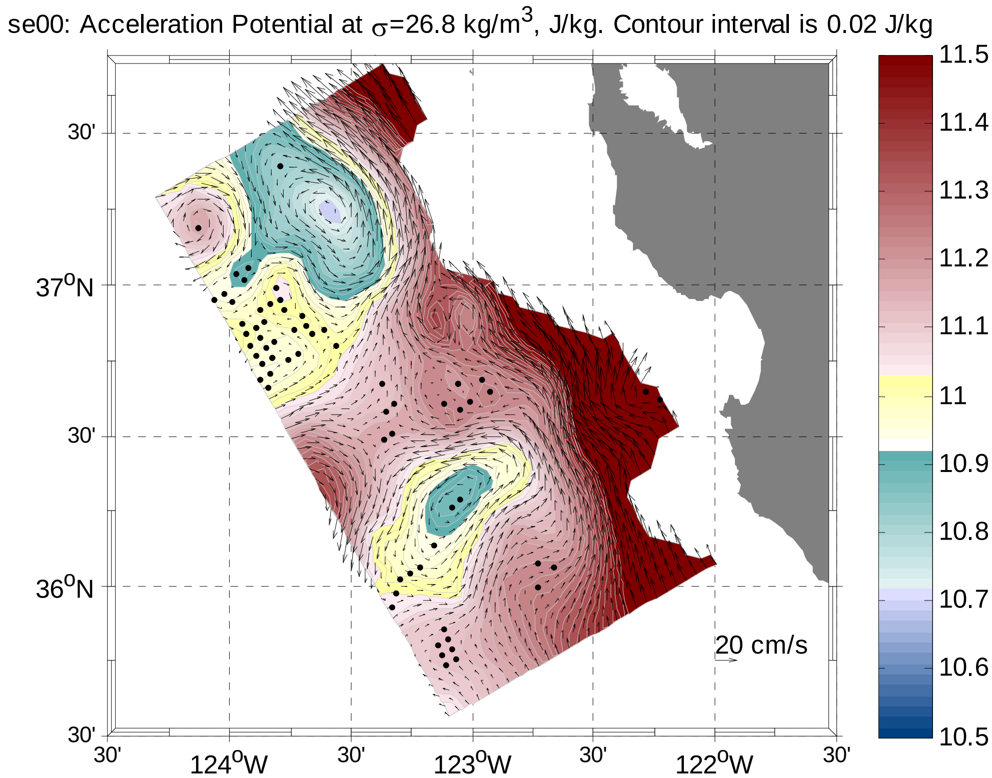


Figure 60. Acceleration potential in J/kg during September 2000 on the 26.8 kg/m^3 density surface. Contour interval is 0.02 J/kg

5. Sea Surface Height – Geopotential and SSHA

The largest magnitude of geopotential (>13.5 J/kg) occurred along the northwest and southwest edges of the survey area (Figure 61, upper). The most prominent feature was the increasing geopotential moving outward in all directions from minimum geopotential (~12.3 J/kg) located near36°45´N, 123°45´W, evidence of westward flow to the north of the minimum and eastward flow to the south. Offshore southern Monterey

Bay, a region of high dynamic height existed (~13.2 J/kg), indicating a second region of westward and eastward flow bands to the south.

As previous comparisons with MSLA, the large scale pattern for September 11, 2000 resembled that shown by dynamic height (Figure 61, lower). A negative anomaly extended from the western boundary through the center of the survey area, with a minimum of negative -5to -8 centimeters. At the southwest and northwest portions of the survey area a steep increase in MSLA (5-7 cm) occurred. But note that the narrow ridge off southern Monterey Bay was not seen, possibly due to its small (25 km) scale. Again, the range of MSLA, 15 cm, compared favorably to that of dynamic height, 12 cm.

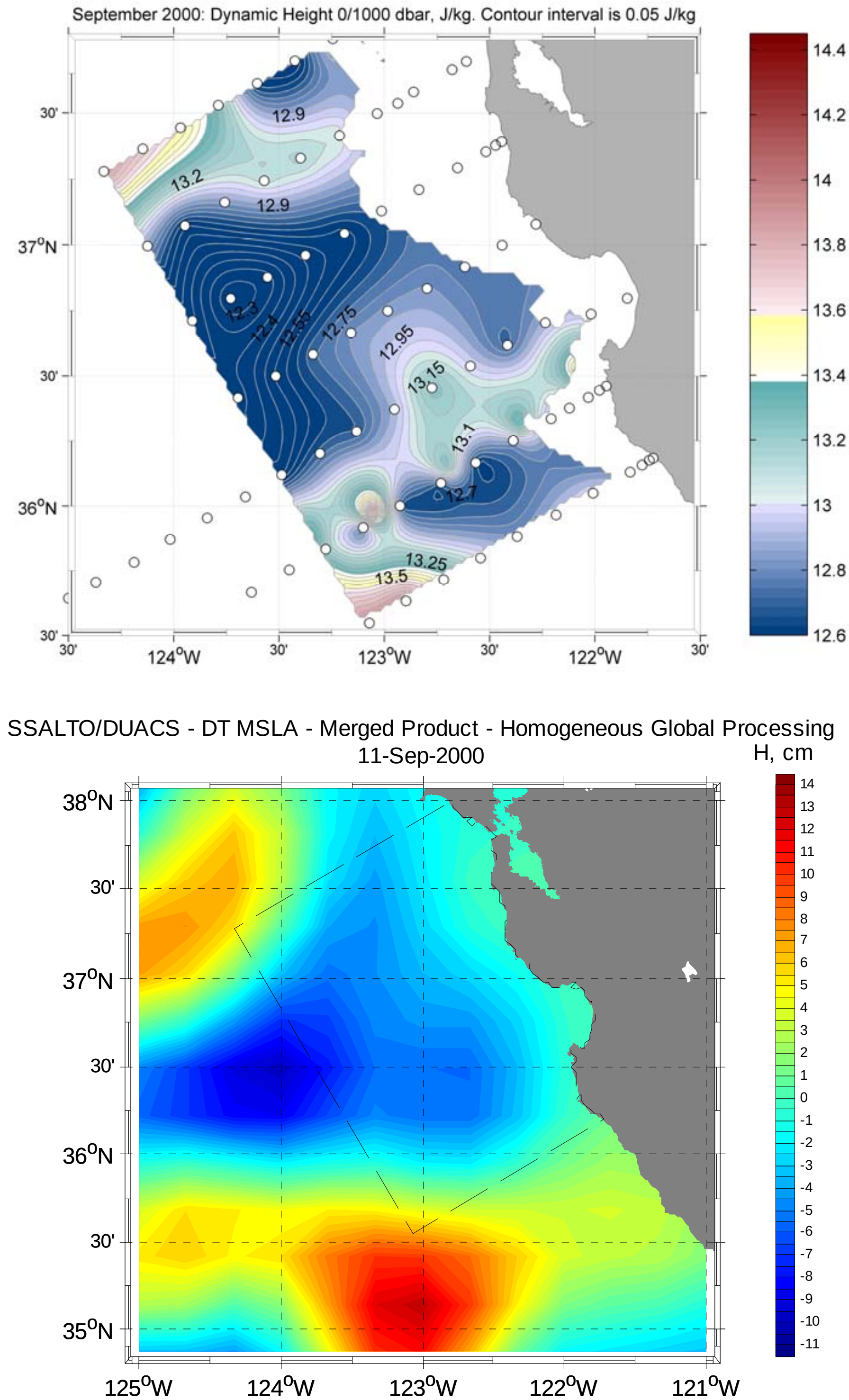


Figure 61. Geopotential (Dynamic Height) in J/kg for September from 0–1000 dbar (upper) and SSHA in cm (daily mean from 08 May). Contour interval is 0.05 J/kg. (upper) and 0.5 cm (lower)

H. MAY 2001

This survey was done by *R/V New Horizon*, which departed Redwood City at 1519Z, 12 May. CTD observations (and the first 24-hour time series) began at 2110Z, 12 May, at 37°32.11´N, 122°56.73´W in depth 111.2 m (CTD station positions shown in figure 62). The second time series began at 0030Z, 14 May, at 37°47.22´N, 123°14.69´W in depth 112.8 m. CTD observations along various CalCOFI lines were conducted from 0408Z, 15 May, to 1317Z, 18 May. A third time series began at 1400Z, 18 May, at 36°47.76´N, 121°50.80´W in depth 247.2 m. Further CTD observations along CalCOFI lines were conducted from 1648Z 19 May, to 1459Z, 23 May. The vessel arrived in Redwood City at 1405Z, 24 May.

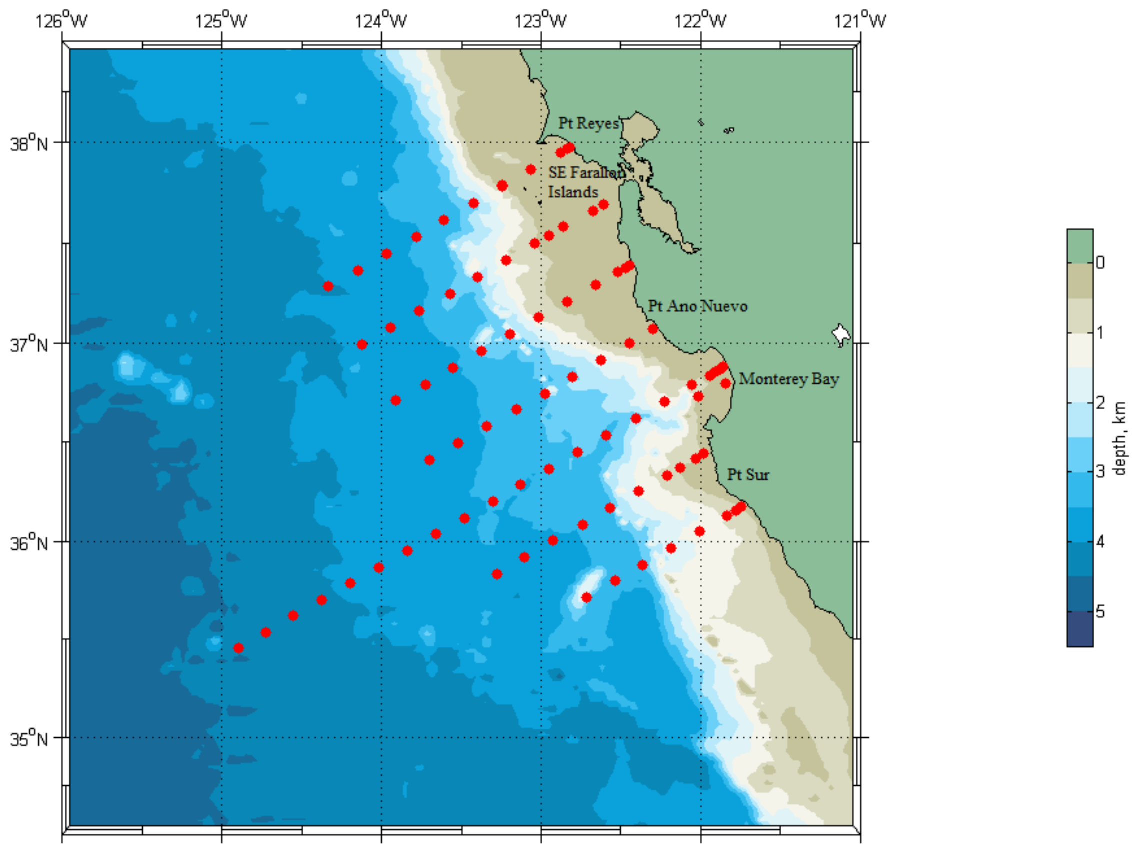


Figure 62. Station positions for May 2001 (shown by red dots).

1. T/S Diagram

The range of spiciness and associated water properties observed for the May 2001 cruise is shown by the black dots in figure 49. Spiciness (potential temperature, salinity) ranged from approximately -0.20 kg/m^3 (8.7°C, 33.55) to 0.40 kg/m^3 (10.6°C, 33.90) on the 26.0 kg/m^3 density surface. For the deeper 26.8 kg/m^3 density surface, spiciness (potential temperature, salinity) ranged from -0.25 kg/m^3 (5.7°C, 34.03) to 0.05 kg/m^3 (7.0°C, 34.20). Sea surface temperatures ranged from 13°C to 14.5°C and sea surface salinities from 33.2 to 34.0.

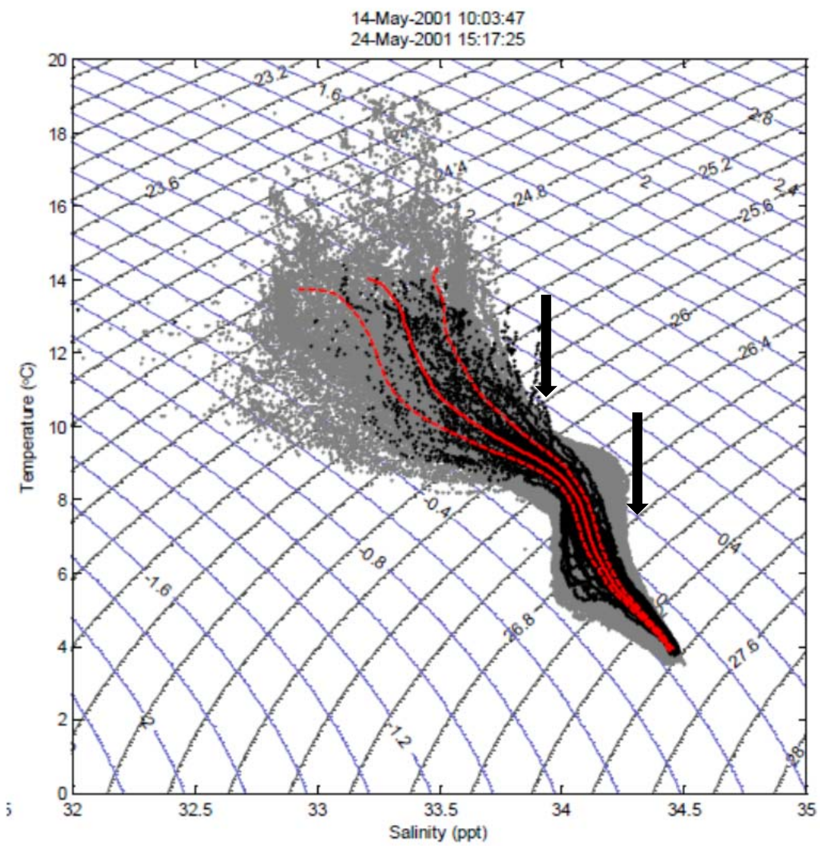


Figure 63. T/S Diagram for May 2001. Black dots are data from the May 2001 cruise, and grey dots represent data from all 10 NAVO cruises. The solid (dashed) red line is the mean (± one standard deviation) of salinity as a function of potential temperature for all 10 NAVO cruises. Density anomalies are shown on the curved lines that slope upward to the right and spiciness is shown by the curved lines that slope downward to the right. Black arrows designate 26.0 and 26.8 kg/m^3 density surfaces.

2. Pressure

Pressure on the 26.0 kg/m^3 isopycnal indicated minimum pressure in the northeast portion of the survey area (Figure 64, upper). Here the isopycnal is at, or nearly at the ocean surface, as minimum pressure levels ranged between 3 and 9 dbar. South and southwest of the this, there was a distinct increasing pressure gradient, where maximum pressure ranges between 105 and 110 dbar.

On the 26.8 kg/m^3 isopycnal, there was a distinct region of larger pressure levels along the eastern edge of the survey area, where pressures increased from 359 dbar to approximately 400 dbar in a sharp gradient. In the northwest and center of the survey region were the lowest pressure levels, where minimum pressure ranged between 317–326 dbar. A region of higher pressure existed at the western limit of the survey between 36°30´N and 37°00´N, where pressure ranged from 359 dbar to near the maximum at the coast, 400 dbar.

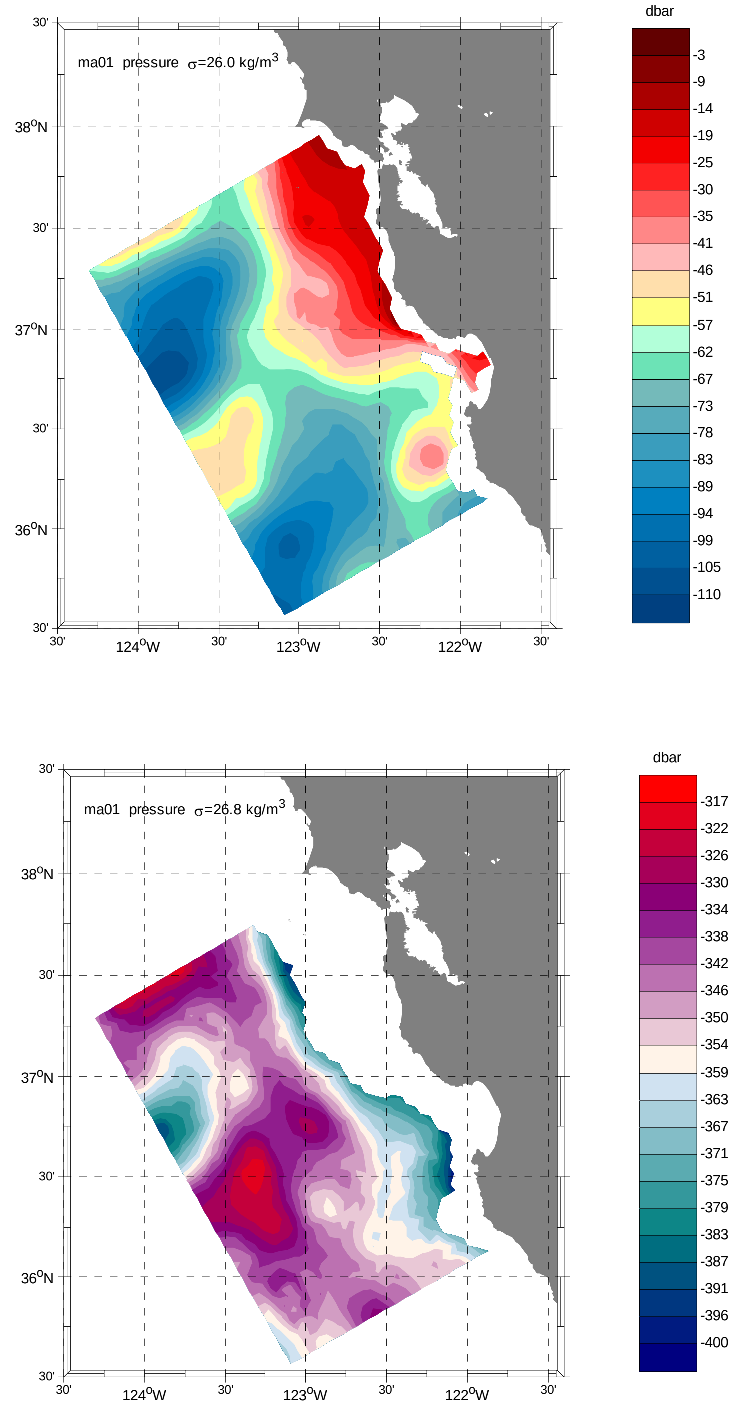
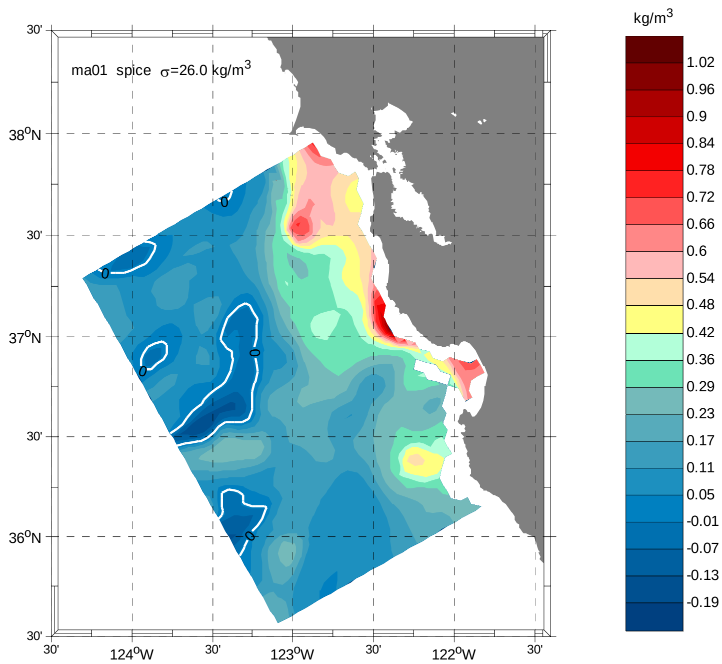


Figure 64. Pressure in dbar during May 2001 for the 26.0 kg/m^3 (upper) and 26.8 kg/m^3 density surfaces (lower). Contour interval is 5.35 dbar (upper) and 4.15 dbar (lower).

3. Spiciness

Spiciness on the 26.0 kg/m^3 isopycnal were positive through much of the survey area, with some isolated regions of near zero spiciness west of 123°W (Figure 65, upper). In the northeast region, spiciness levels generally ranged between 0.42 kg/m^3 and 1.02 kg/m^3. These spiciness levels occurred in the same region close to the coast, where lower pressure was seen in previous figures.

On the 26.8 kg/m^3 isopycnal, the zero spiciness contour meanders in a north-south direction between 123°W and 123°30´W. This separated a region of negative spiciness on the western part of the survey area from one of positive spiciness in the east. The location of minimum spiciness levels (-0.14 to -0.16 kg/m^3) was in the same latitude region (between 36°30´N and 37°00´N) as the maximum spiciness levels close to the coast (0.21-0.23 kg/m^3).



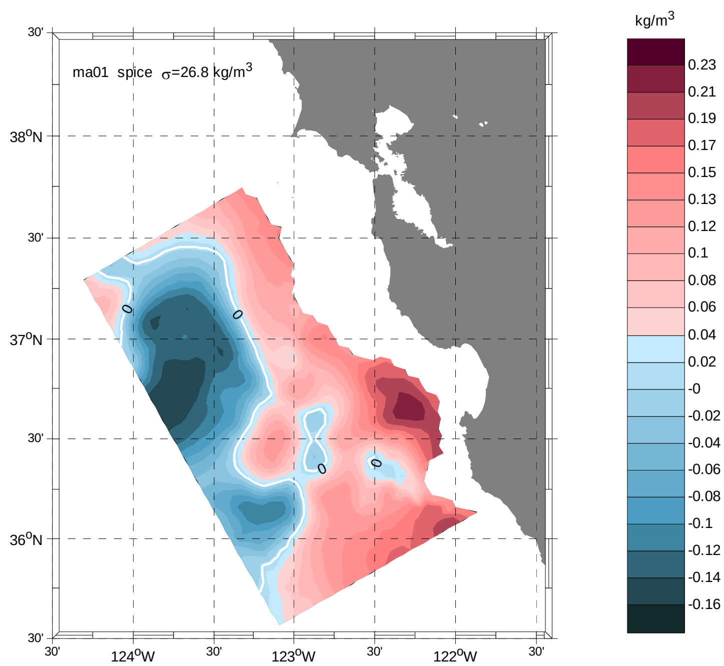


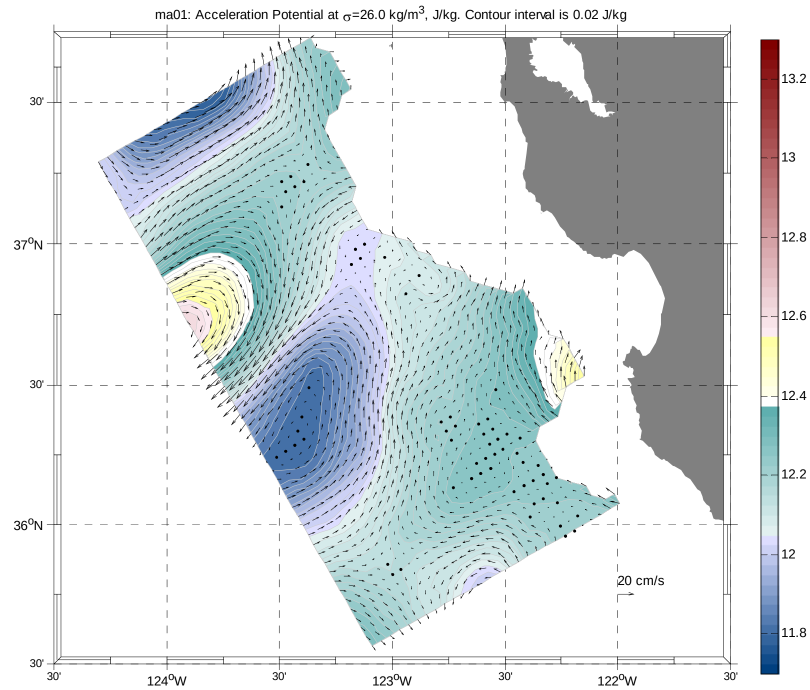
Figure 65. Spiciness in kg/m^3 during May 2001 for the 26.0 kg/m^3 (upper) and 26.8 kg/m^3 (lower) density surfaces. Contour interval is 0.06 kg/m^3 (upper) and 0.02 kg/m^3 (lower). White denotes zero spiciness contour.

4. Acceleration Potential and ADCP

Acceleration potential on the 26.0 kg/m^3 isopycnal during the May 2001 survey was marked by a series of ridges and troughs of acceleration potential from south to north. Ridges of acceleration potential extended along 123°00´W in the east and near 37°0´N in the north, each of which was bounded by an area of lower acceleration potential. Poleward flow occurred inshore, east of 123°W (Figure 66, upper). Flow was onshore north of 37°N. A region of a stronger anticyclonic flow was seen on the western boundary at 36°45´N, 123°57´W.

The ADCP velocity field on the 26.0 kg/m^3 isopycnal indicated some equatorward flow near shore off Pt. Año Nuevo, shifting to poleward flow further offshore (Figure 66, lower). This poleward flow became entrained in eddy-like flow features north of 37°N. Flow through other areas of the survey area was variable.

The acceleration potential on the 26.8 kg/m^3 isopycnal indicated a large cyclonic feature centered at 36°57´N, 123°45´W. This feature appears to separate poleward inshore flow (seen throughout the eastern portion of the survey area) from equatorward flow to the west. Flow throughout the southern, southwestern portion of the survey area was weak and variable.



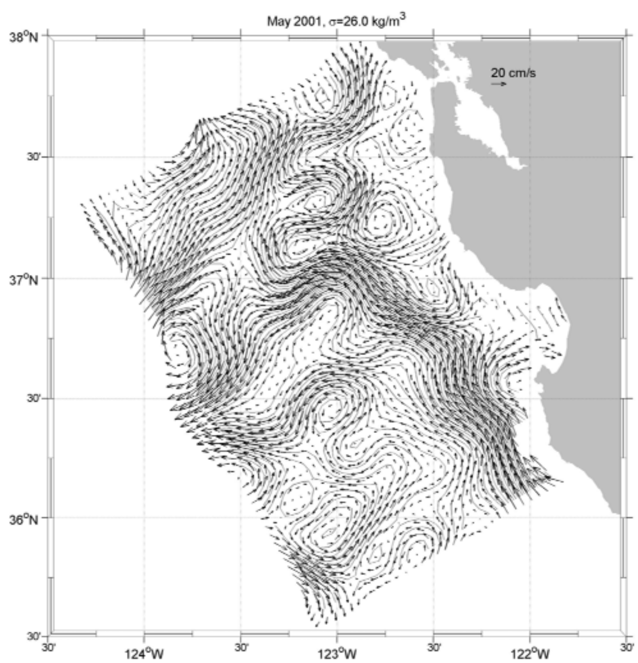


Figure 66. Acceleration potential in J/kg during May 2001 (upper) and ADCP velocities in cm/s (lower) for the 26.0 kg/m^3 density surface. Contour interval is 0.02 J/kg (upper) and the magnitude of flow is given by the arrow shown in the upper right corner (lower).

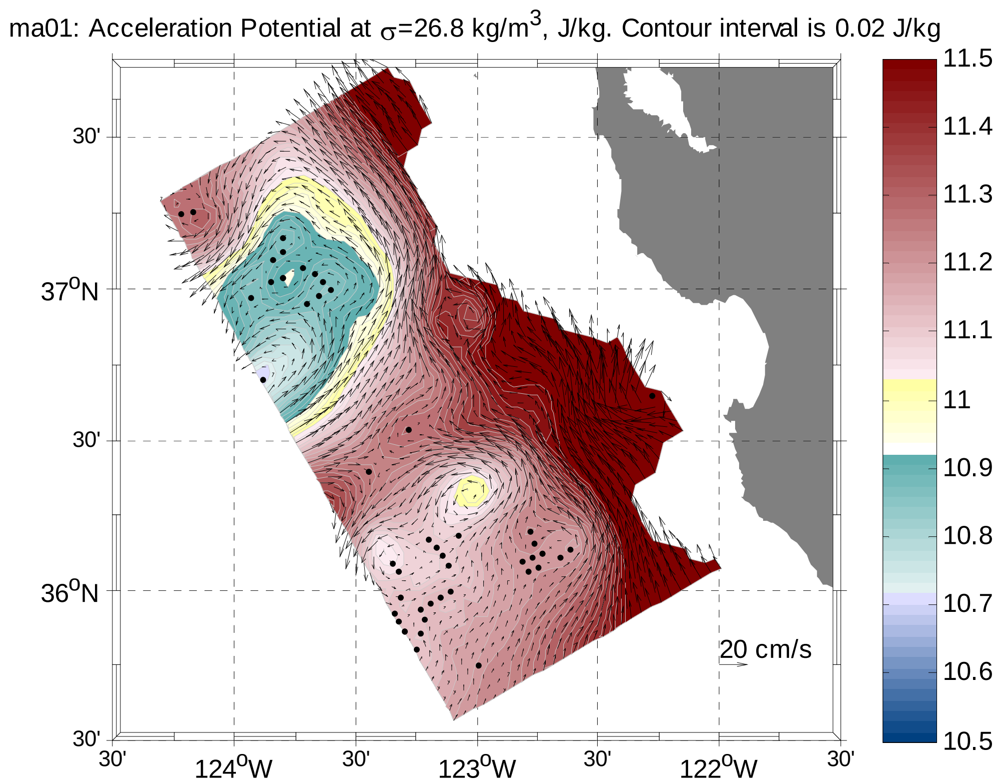


Figure 67. Acceleration potential in J/kg during May 2001 on the 26.8 kg/m^3 density surface. Contour interval is 0.02 J/kg

5. Sea Surface Height – Geopotential and SSHA

Geopotential (dynamic height) indicated a maximum of geopotential, ~13.1 J/kg, occurred near 36°45′N, 123°55′W and extended inshore to the coast (Figure 68, upper). Since the minimum in geopotential (<12.25 J/kg) occurs on the northern edge of the survey area, flow in the region between these two features was directed offshore. There was also a region of lower geopotential through the center of survey area (<12.3 J/kg) also extending to the coast. To the south, a second ridge of dynamic height extended to the coast. This continued the zonal pattern of onshore-offshore flow through the region.

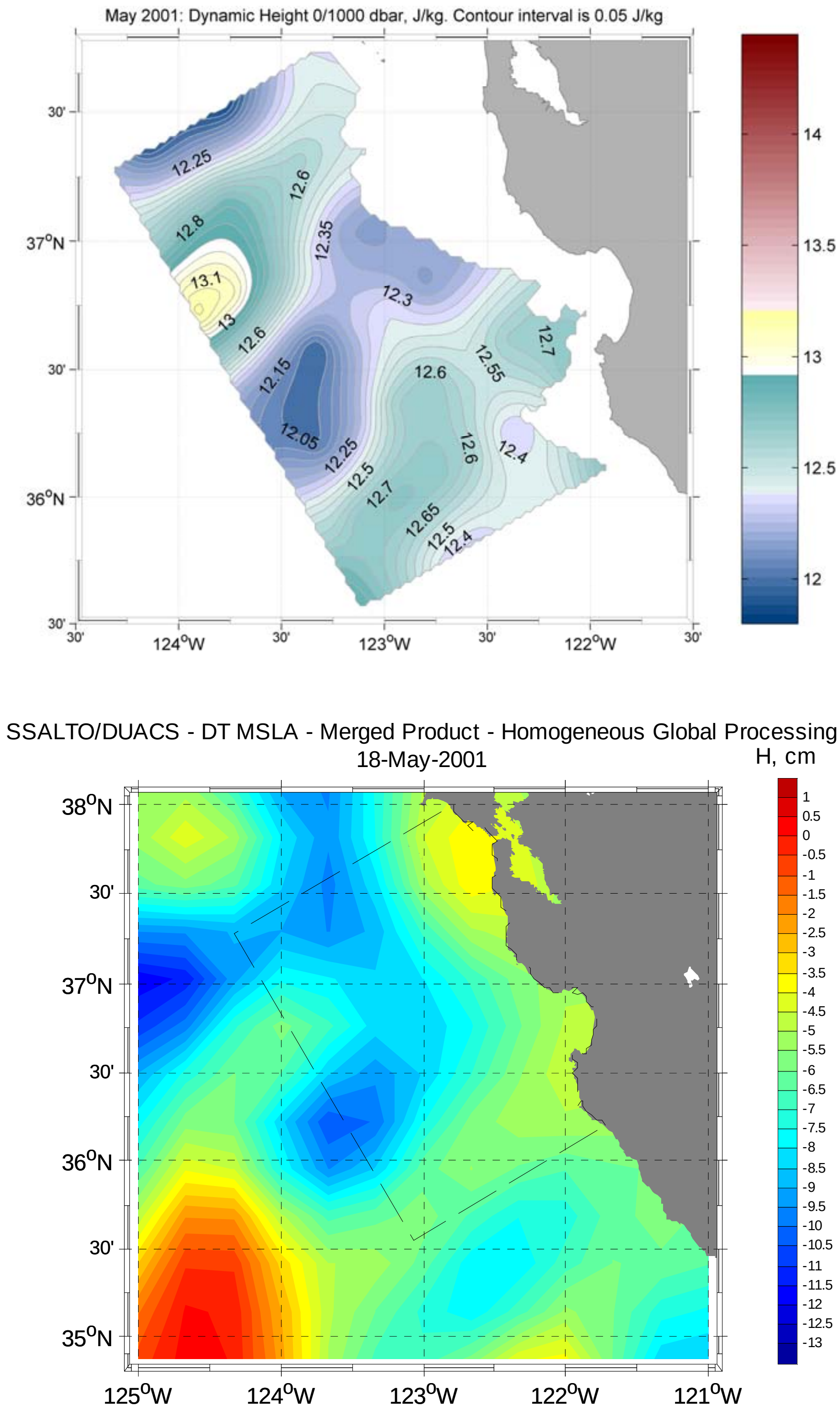


Figure 68. Geopotential (Dynamic Height) in J/kg for September from 0–1000 dbar (upper) and SSHA in cm (daily mean from 08 May). Contour interval is 0.05 J/kg. (upper) and 0.5 cm (lower).

Unlike the previous survey, MSLA reproduced both ridges and troughs which extended through the survey region on 18 May 2001 (Figure 68, lower). A MSLA minimum of -10 to -11 centimeters was centered around 36°14′N, 123°17′W and a maximum of 9-10 centimeters was observed in the northern survey area near 37°30′N, 123°17′W.

I. DECEMBER 2001

This survey was done by *R/V Point Sur* which departed Moss Landing at 1629Z, 28 November. CTD observations (and the first 24-hour time series) began at 0846Z, 29 November, at 37°48.93′N, 122°28.49′W in depth 95.8 m (location of CTD stations is shown in Figure 69). CTD observations along CalCOFI line 60 began at 1232Z, 30 November at 37°58.50′N, 122°49.21′W in depth 23 m and ended at 0415Z, 1 December. CTD observations were begun along line 61.5 at 0706Z, 1 December, but interrupted due to weather. A second time series was begun at 0043Z, 2 December, at 37°49.14′N, 122°27.94′W in depth 84.9 m. On 2 December the vessel arrived in San Francisco. The survey was resumed at 1454Z, 3 December and CTD observations along line 61.5 commenced at 1748Z, 3 December, ending at 2102Z, 3 December. A third time series was begun at 0611Z, 4 December at 36°47.63′N, 121°50.82′W in depth 294.1 m. CTD observations along various CalCOFI lines were conducted from 1141Z 5 December to 0954Z 7 December. *Point Sur* arrived at Moss Landing at 1449Z, 7 December, departing at 1712Z to resume the survey. Further CTD observations were conducted from 1809Z, 7 December to 1907Z, 11 December. *Point Sur* returned to Moss Landing at 2057Z, 11 December.

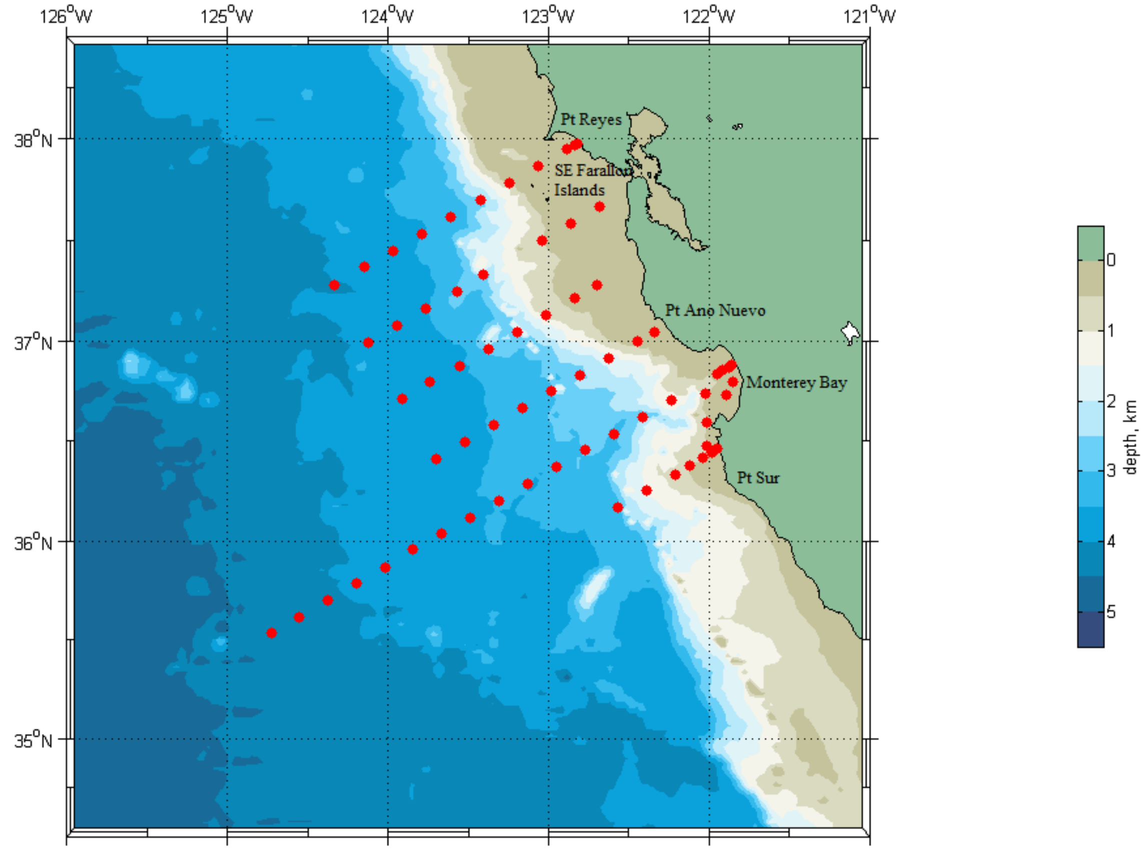


Figure 69. Station positions for December 2001 (shown by red dots).

1. T/S Diagram

The range of spiciness and associated water properties observed for the December 2001 cruise is shown by the black dots in Figure 70. Spiciness (potential temperature, salinity) ranged from approximately 0.0 kg/m^3 (9.3°C, 33.55) to 0.20 kg/m^3 (10.2°C, 33.75) on the 26.0 kg/m^3 density surface. For the deeper 26.8 kg/m^3 density surface, spiciness (potential temperature, salinity) ranged from -0.20 kg/m^3 (5.7°C, 34.05) to 0.05 kg/m^3 (7.0°C, 34.25). Sea surface temperature ranged from 10°C-14°C and sea surface salinity from 32.8 to 33.5

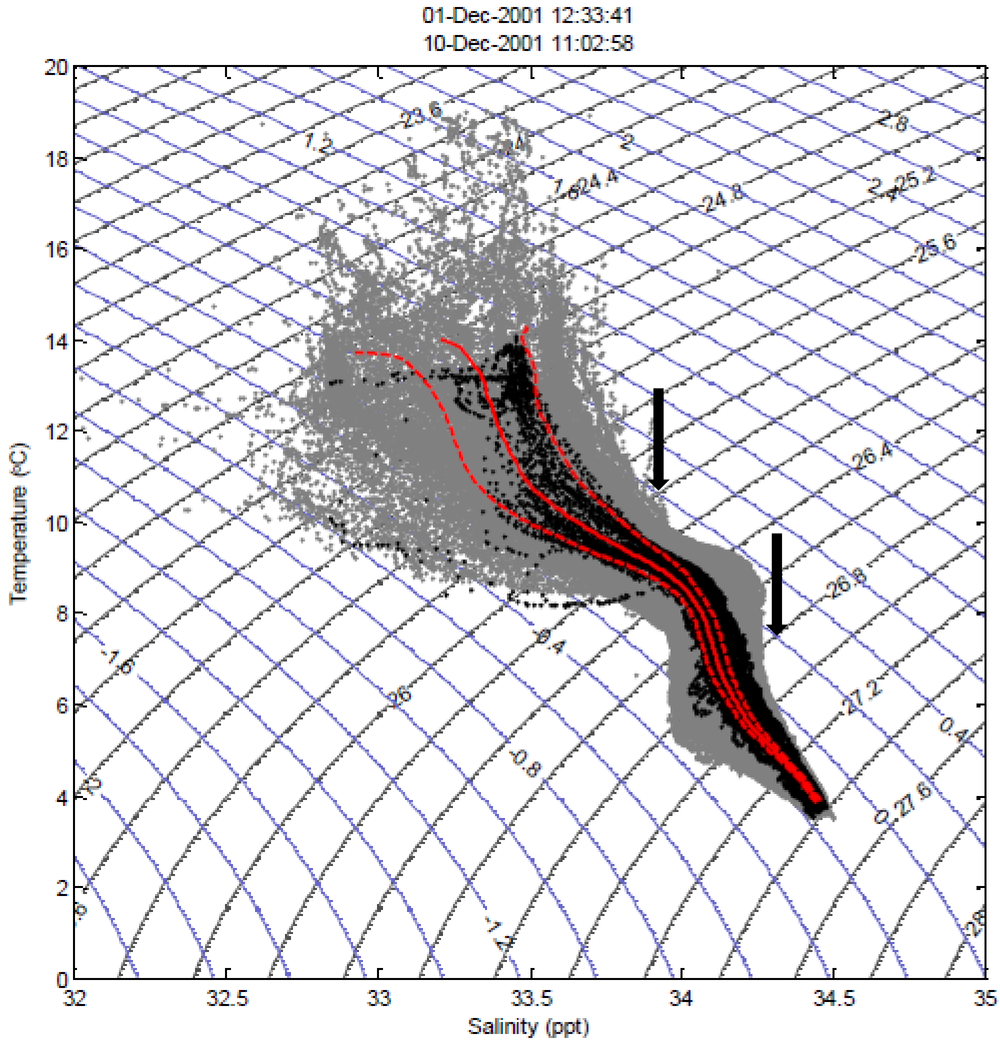


Figure 70. T/S Diagram for December 2001. T/S Diagram for May 2001. Black dots are data from the May 2001 cruise, and grey dots represent data from all 10 NAVO cruises. The solid (dashed) red line is the mean (± one standard deviation) of salinity as a function of potential temperature for all 10 NAVO cruises. Density anomalies are shown on the curved lines that slope upward to the right and spiciness is shown by the curved lines that slope downward to the right. Black arrows designate 26.0 and 26.8 kg/m^3 density surfaces.

2. Pressure

Pressure on the 26.0 kg/m^3 isopycnal indicated a clear north to south gradient of increasing pressure (Figure 71, upper). The minimum pressure, 63–68 dbar, occurred nearly in the center of the survey area, centered near 36°45´N, 123°10´W. This pressure ridge extended from the offshore, northern limit southwestward, intersecting the coast at 36°30´N. South of this latitude, pressure steadily increased to maximum of 143–147 dbar in the southern corner of the survey area.

On the 26.8 kg/m^3 isopycnal, there was an area of minimum pressure centered at 36°58´N, 123°52´W, where pressure ranged between 335–342 dbar (Figure 71, lower).. Pressure ridges extended northwestward, eastward, and southward from this minimum,. Maximum pressure of 398–401 dbar was located in the vicinity of 36°00´N, 122°30´W, and also near the coast at 37°30´N.

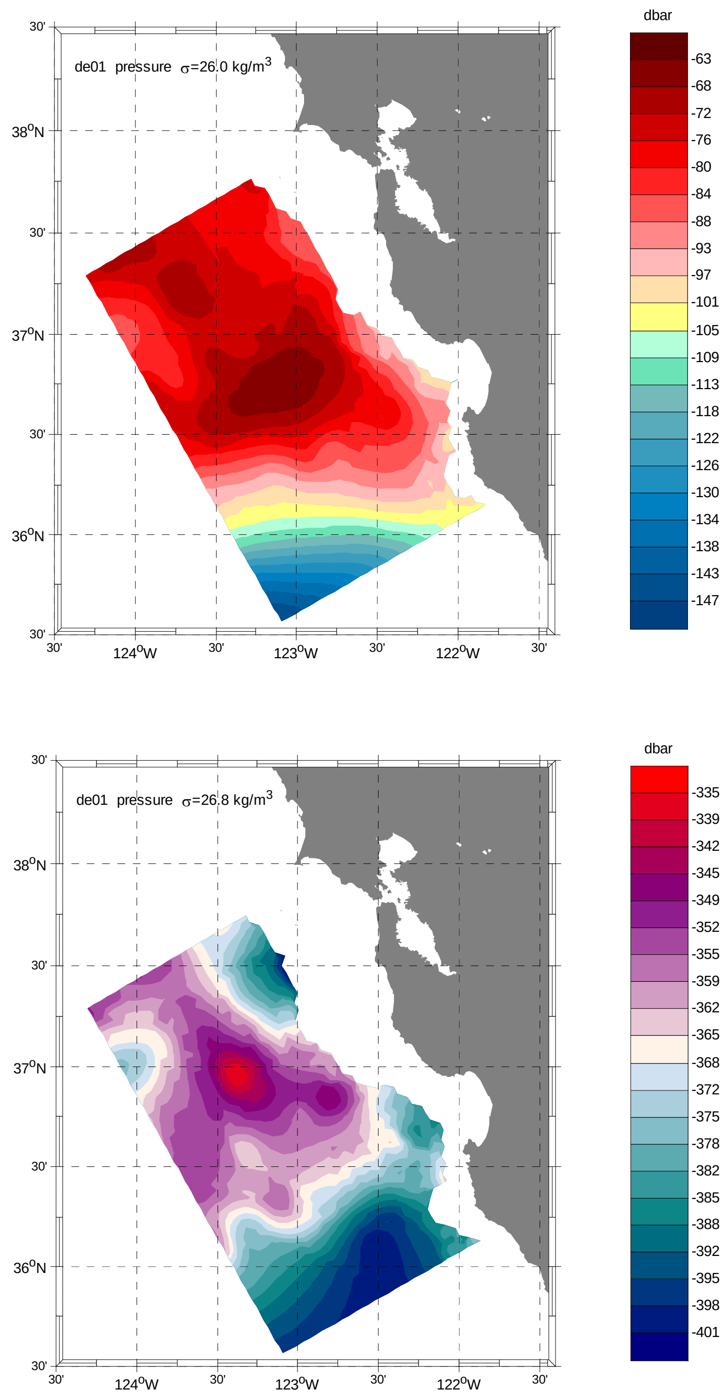


Figure 71. Pressure in dbar during December 2001 for the 26.0 kg/m^3 (upper) and 26.8 kg/m^3 density surfaces (lower). Contour interval is 4.20 dbar (upper) and 3.30 dbar (lower).

3. Spiciness

Spiciness on the 26.0 kg/m^3 isopycnal was positive over much of the survey area (Figure 72, upper). An exception occurred in the western part of the survey area, where the largest area enclosed by the zero spiciness contour was centered at 36°13′N, 123°22′W. The 0.2 kg/m^3 spiciness contour followed the 123°06′W meridian, but mesoscale features appeared throughout the survey region.

Spiciness on the 26.8 kg/m3 isopycnal shows a zero spiciness contour meandering north-south between 123°W and 123°30′W, separating negative spiciness levels in the west from negative spiciness levels in the east. Overall minimum spiciness levels of -0.12 kg/m^3 to -0.16 kg/m^3 are centered around 36°45′N, 123°44′W, while maximum spiciness levels of 0.19 kg/m^3 to 0.23 kg/m^3 are centered around 36-34°N, 122-46°W (at the entrance to Monterey Bay).

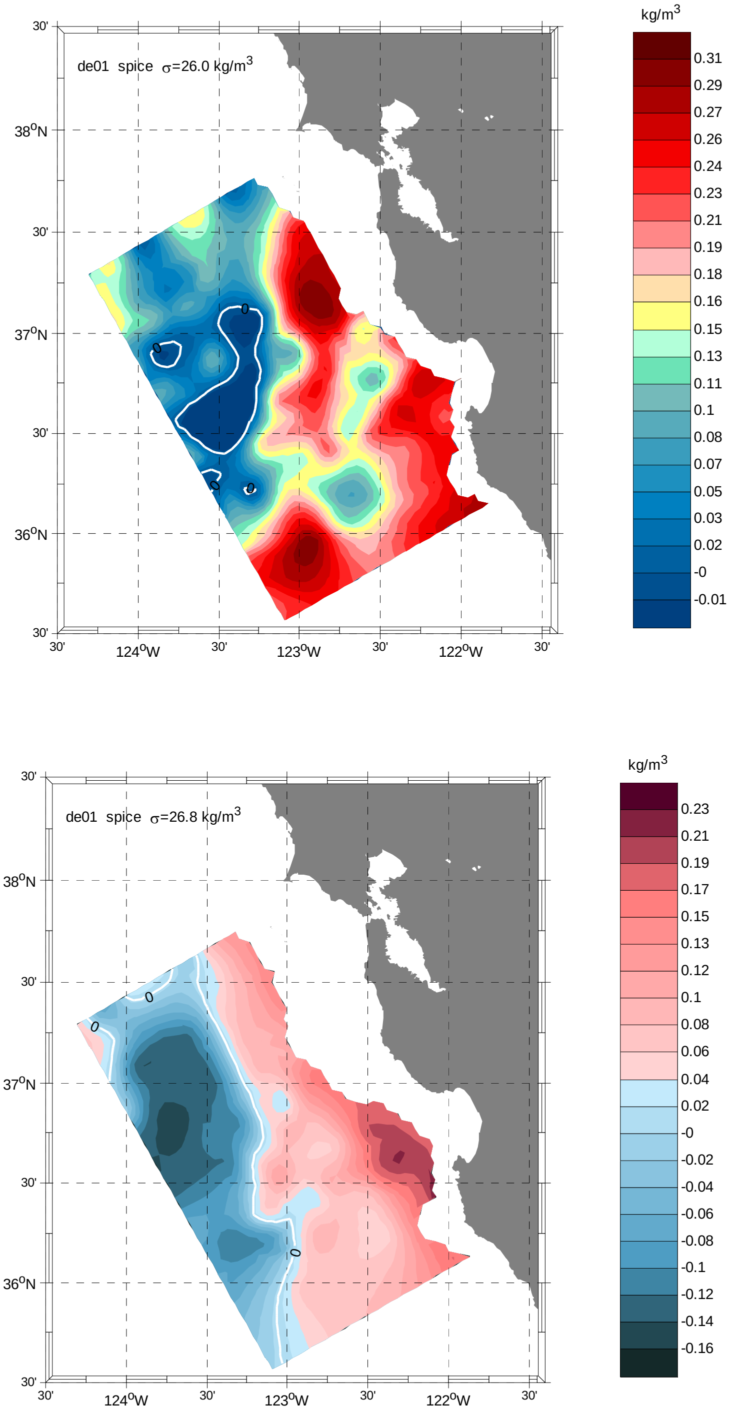
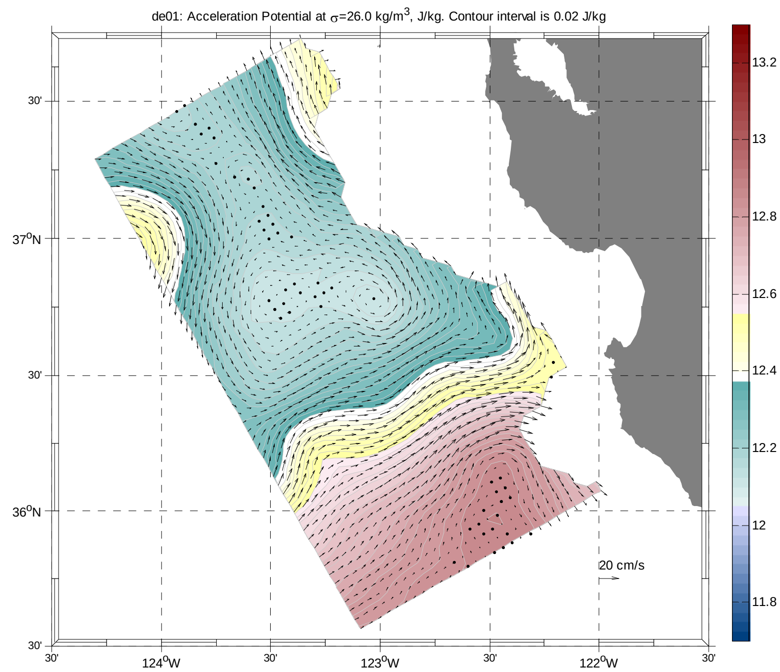


Figure 72. Spiciness in kg/m^3 during December 2001 for the 26.0 kg/m^3 (upper) and 26.8 kg/m^3 (lower) density surfaces. Contour interval is 0.016 kg/m^3 (upper) and 0.019 kg/m^3 (lower). White denotes zero spiciness contour.

4. Acceleration Potential and ADCP

Acceleration potential on the 26.0 kg/m^3 isopycnal during the December 2001 survey (Figure 73, upper) was similar to that seen during the November 1998 survey. A region of large acceleration greater than 12.4 J/kg was located in the southern portion of the survey area while a region of acceleration potential less than 12.4 J/kg filled most of the northern region. As a consequence, a broad region about 110 km wide of onshore flow existed across the entire survey region near 36°30′N. North of 37°N, meridional flows occurred, equatorward offshore (the CC) and poleward inshore (the IC).

ADCP velocities indicated some poleward inshore flow at and north of 37°N. Along the western boundary at this same latitude there was visible equatorward flow. Throughout the rest of the survey flow was variable and eddy-like.



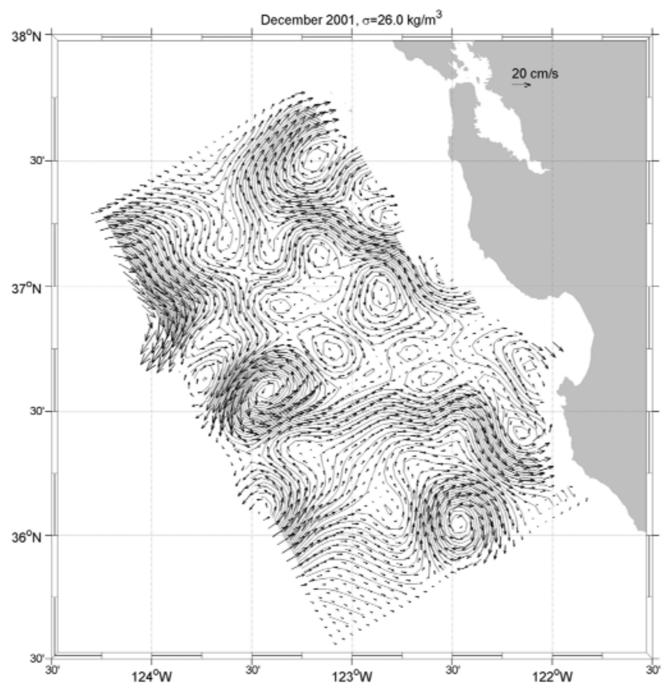


Figure 73. Acceleration potential in J/kg during December 2001 (upper) and ADCP velocities in cm/s (lower) for the 26.0 kg/m^3 density surface. Contour interval is 0.02 J/kg (upper) and the magnitude of flow is given by the arrow shown in the upper right corner (lower).

The display of acceleration potential on the 26.8 kg/m^3 isopycnal (Figure 74) showed poleward inshore flow to be clearly visible in the eastern part of the survey area. West of this, there were cyclonic flow features offshore to the north and south that appeared to recirculate poleward inshore flow and equatorward offshore flows.

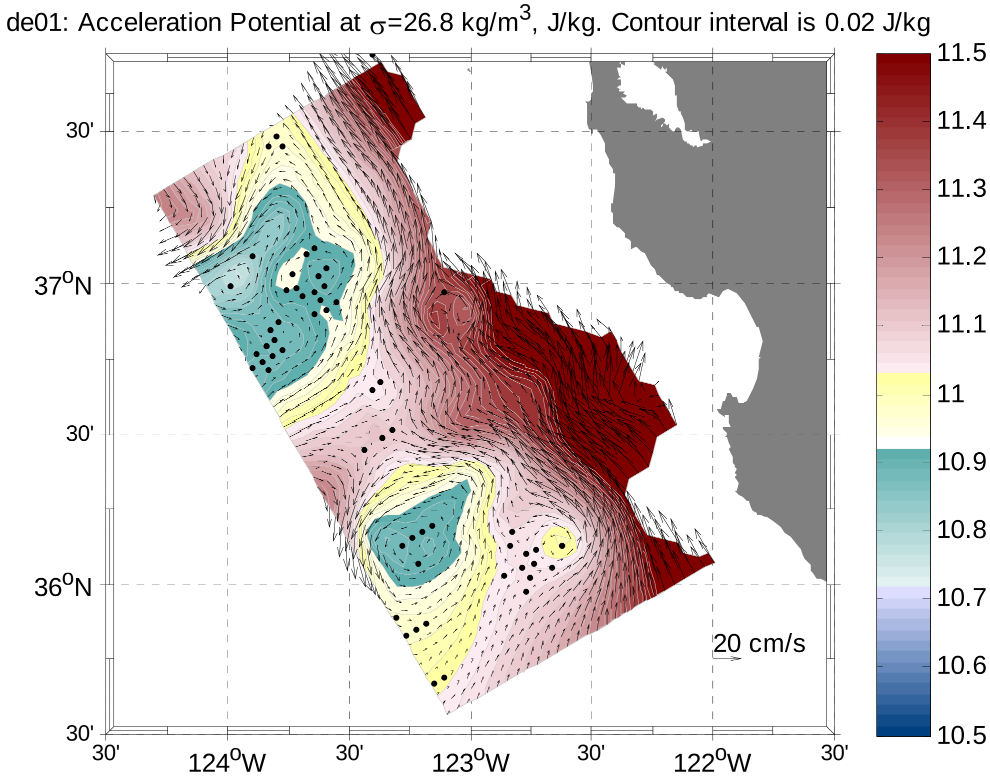


Figure 74. Acceleration potential in J/kg during December 2001 on the 26.8 kg/m^3 density surface. Contour interval is 0.02 J/kg

5. Sea Surface Height – Geopotential and ADCP

The maximum in geopotential (~13.8 J/kg) occurred on the southern edge of the survey area (Figure 75, upper). Geopotential decreased to the north to near 36°45´N, 123°15´W where the minimum (<12.55 J/kg) was located. Between the minimum and maximum geopotential, geostrophic surface flow relative to 1000 dbar was directed onshore. A trough in geopotential extended to the northwest with maximum appearing at both the inshore (12.95 J/kg) and offshore (13.65 J/kg) boundaries.

MSLA (taken from median cruise day 5 December) indicated that sea surface elevation decreased from the south, +3 cm, to northwest, -9 cm, through the survey area (Figure 75, lower). This was the general pattern for geopotential but the latter indicated the maximum to be further offshore and the maximum to be near the center of the survey region. Note that the range of MSLA variability, 12 cm, was close to that of geopotential, 0.13 J/kg.

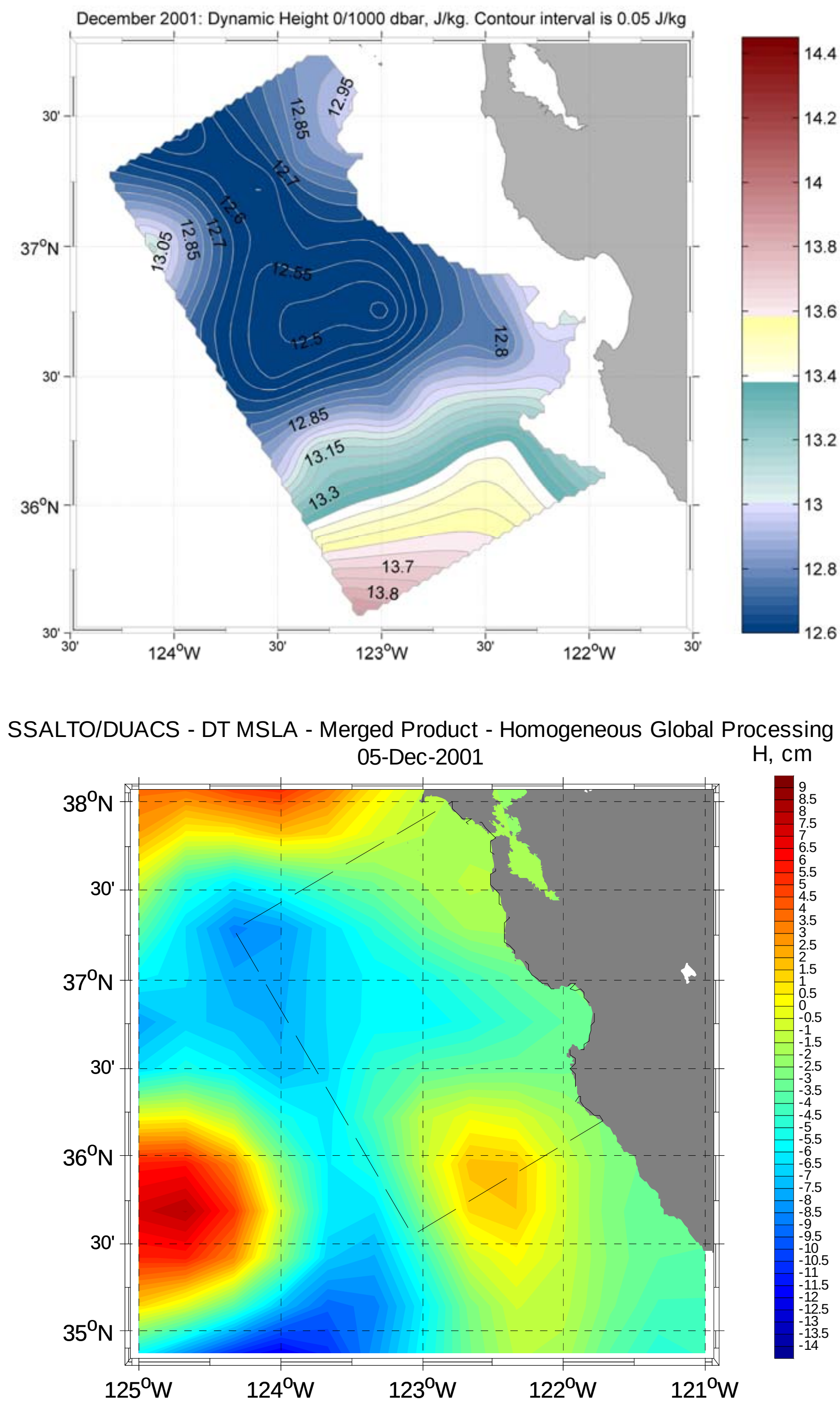


Figure 75. Geopotential (Dynamic Height) in J/kg for December 2001 from 0–1000 dbar (upper) and SSHA in cm (daily mean from 05 December). Contour interval is 0.05 J/kg. (upper) and 0.5 cm (lower).

J. NOVEMBER 2002

This survey was done by *R/V Point Sur,* which departed Moss Landing at 1638Z, 5 November. CTD observations began at 0055Z, 6 November (CTD station locations shown in Figure 76). The first time series began at 1529Z, 7 November, at 37°49.05´N, 122°28.43´W, in depth 86 m. Leg one of the cruise concluded at 1750Z, 8 November. CTD observations resumed at 1928Z, 10 November at 37°17.52´N, 122°39.09´W and concluded at 0017Z, 12 November, with leg two concluding shortly thereafter. CTD observations again resumed at 0047Z, 12 November and continued until 1545Z, 15 November, with the end of leg three shortly thereafter. CTD observations resumed at 2010Z, 16 November. A time series began at 1956Z, 18 November, at 36°31.97´N, 121°56.61´W at depth 278 m. CTD observations concluded at 2057Z, 19 November and *Point Sur* returned to Moss Landing at 2359Z. Note that data from this cruise has also been analyzed by O'Malley (2003).

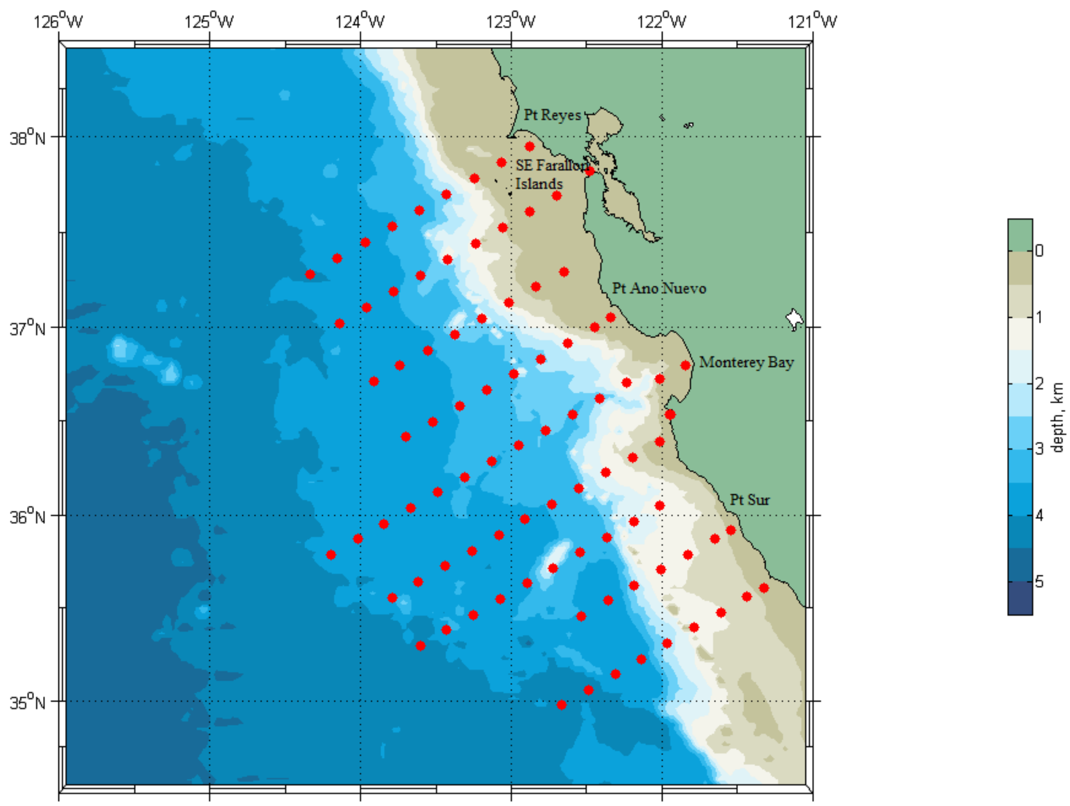


Figure 76. Station positions for November 2002 (shown by red dots).

1. T/S Diagram

The range of spiciness and associated water properties observed for the November 2002 cruise is shown by the black dots in Figure 49. Spiciness (potential temperature, salinity) ranged from approximately -0.3 kg/m^3 (8.4°C, 33.40) to 0.20 kg/m^3 (10.0°C, 33.80) on the 26.0 kg/m^3 density surface. For the deeper 26.8 kg/m^3 density surface, spiciness (potential temperature, salinity) ranged from -0.30 kg/m^3 (5.3°C, 33.95) to 0.00 kg/m^3 (6.9°C, 34.20). Sea surface temperatures ranged from 12°C to 15°C and surface salinities from 32.8 to 33.4. Note that salinities for temperatures between 5°C to 8°C were about 0.1 less than the average for the ten cruises.

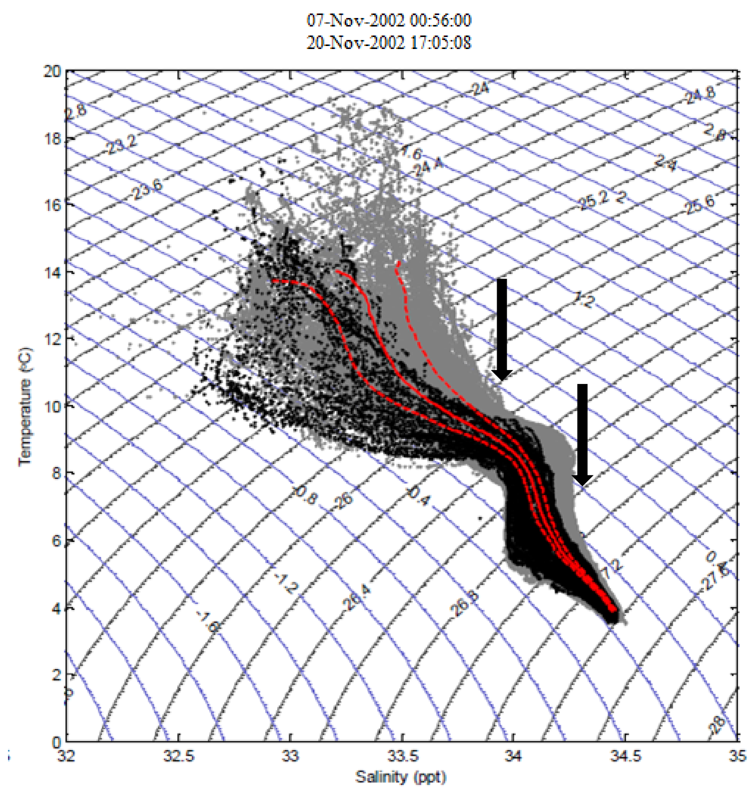
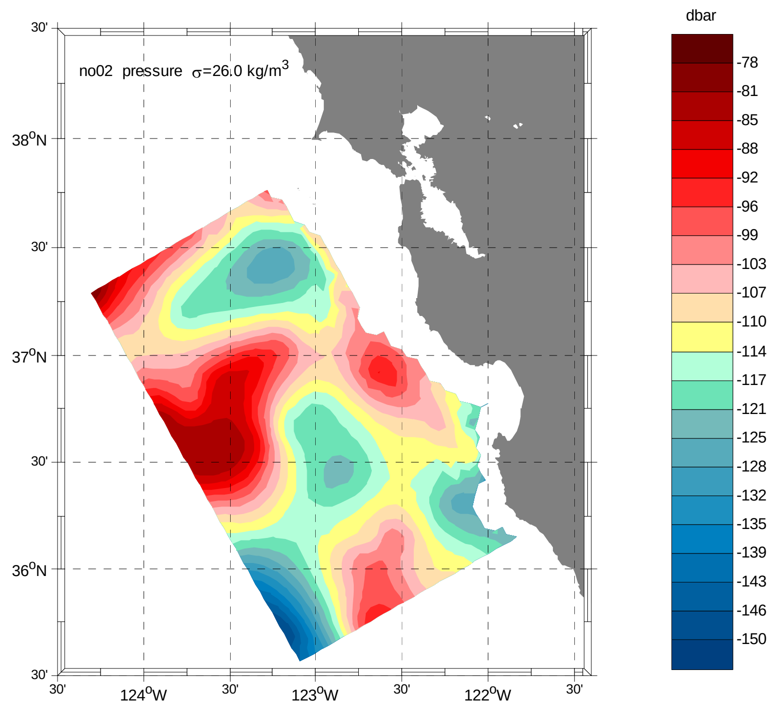


Figure 77. T/S Diagram for December 2001. T/S Diagram for May 2001. Black dots are data from the May 2001 cruise, and grey dots represent data from all 10 NAVO cruises. The solid (dashed) red line is the mean (± one standard deviation) of salinity as a function of potential temperature for all 10 NAVO cruises. Density anomalies are shown on the curved lines that slope upward to the right and spiciness is shown by the curved lines that slope downward to the right. Black arrows designate 26.0 and 26.8 kg/m^3 density surfaces.

2. Pressure

Pressure on the 26.0 kg/m^3 isopycnal indicated a complex, undulating surface (Figure 78, upper). A series of three mesoscale anticyclonic troughs was found along 123°15′W with minimum pressure near the southern corner of the survey. Two mesoscale cyclonic peaks were formed along 122°30′W, but minimum pressure, 81–85 dbar, occurred at 36°22′N, 122°37′W.

On the 26.8 kg/m^3 isopycnal, a region of lower pressure existed in the western part of the survey area (Figure 78, lower). Here pressure ranged from 372–396 dbar. The pressure minima on the ridge was centered at 36°45′N, 123°45′W. Pressure increased towards the coast, with a pressure maximum of 444 dbar in the vicinity of 36°45′N, 122°15′W. Largest pressure gradients were found along the coast offshore Monterey Bay.



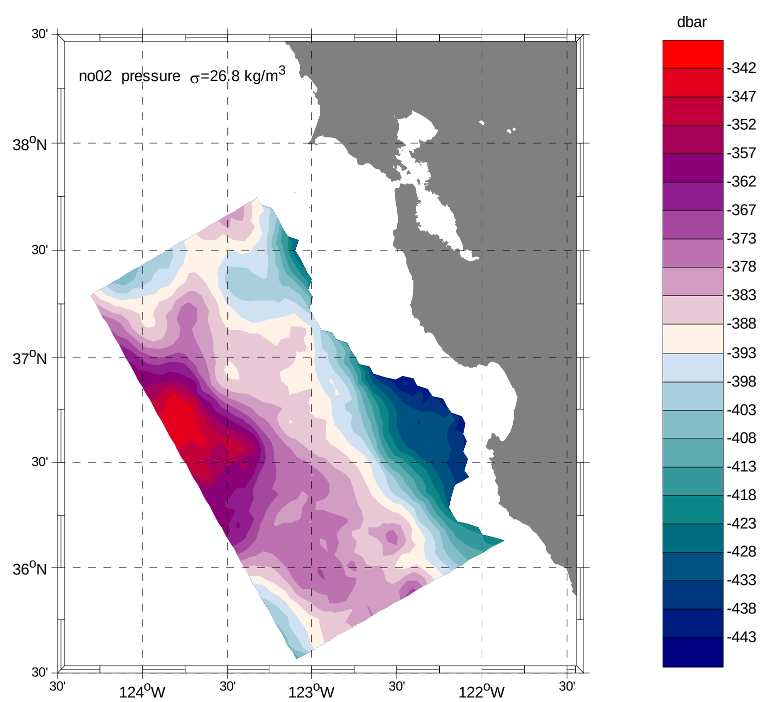


Figure 78. Pressure in dbar during November 2002 for the 26.0 kg/m^3 (upper) and 26.8 kg/m^3 density surfaces (lower). Contour interval is 3.6 dbar (upper) and 5.05 dbar (lower).

3. Spiciness

Spiciness on the 26.0 kg/m^3 isopycnal in the region where lower pressures were noted in the previous figure ranged between -0.05 kg/m^3 and 0.1 kg/m^3(Figure 79, upper). Similar spiciness properties were notable in a north to south region along longitude 123°W. Here, spiciness ranged from 0.17 kg/m^3 to 0.28 kg/m^3. There were two isolated boluses centered at 36°45´N, 122°40´W where spiciness ranged between 0.15 kg/m^3 and 0.10 kg/m^3.

On the 26.8 kg/m3 isopycnal surface, the zero spiciness contour followed the 123°W to 123°30´W meridians, separating low offshore spiciness from higher spiciness inshore waters (Figure 79, lower). In the region away from the coast, spiciness ranged between -0.17 kg/m^3 and 0.0 kg/m^3 The spiciness maximum of around 0.25 kg/m^3 was seen close to the coast.

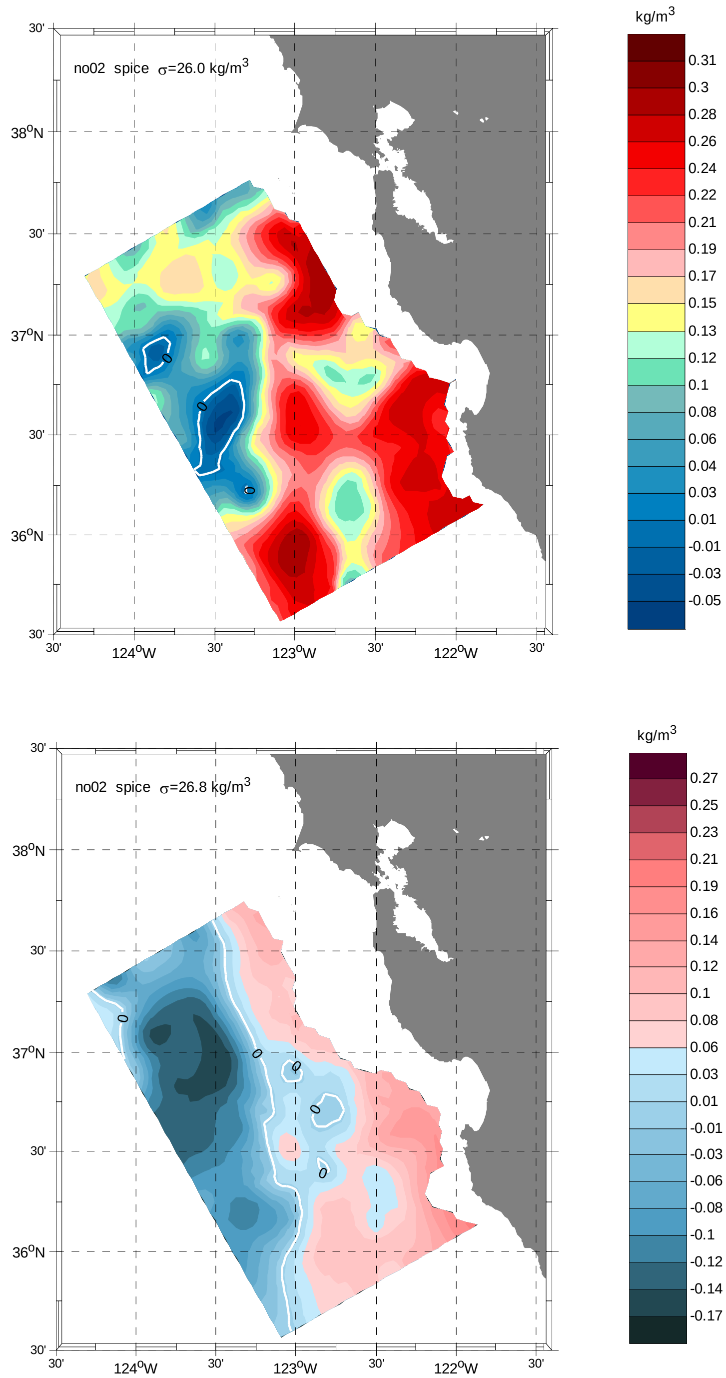


Figure 79. Spiciness in kg/m^3 during November 2002 for the 26.0 kg/m^3 (upper) and 26.8 kg/m^3 (lower) density surfaces. Contour interval is 0.018 kg/m^3 (upper) and 0.022 kg/m^3 (lower).White denotes zero spiciness contour.

4. Acceleration Potential and ADCP

The acceleration potential on the 26.0 kg/m^3 isopycnal for the November 2002 survey (Figure 80, upper) showed a pattern of maximum acceleration potential next to the coast and minimum offshore, opposite to that for May 1998. Maximum acceleration potential occurred off Monterey Bay, 13.2 J/kg and there was poleward directed flow that extended across the entire survey region at 36°30´N. A large region of cyclonic flow corresponding to minimum acceleration potential, 12.1 J/kg, was visible at 36°07´N, 123°45´W. Flow was equatorward at the southwest boundary of the survey area.

ADCP velocities indicated poleward flow east of 123°W (Figure 80, lower). Flow was highly variable moving further west, evidence of the coastal transition zone within the CCS.

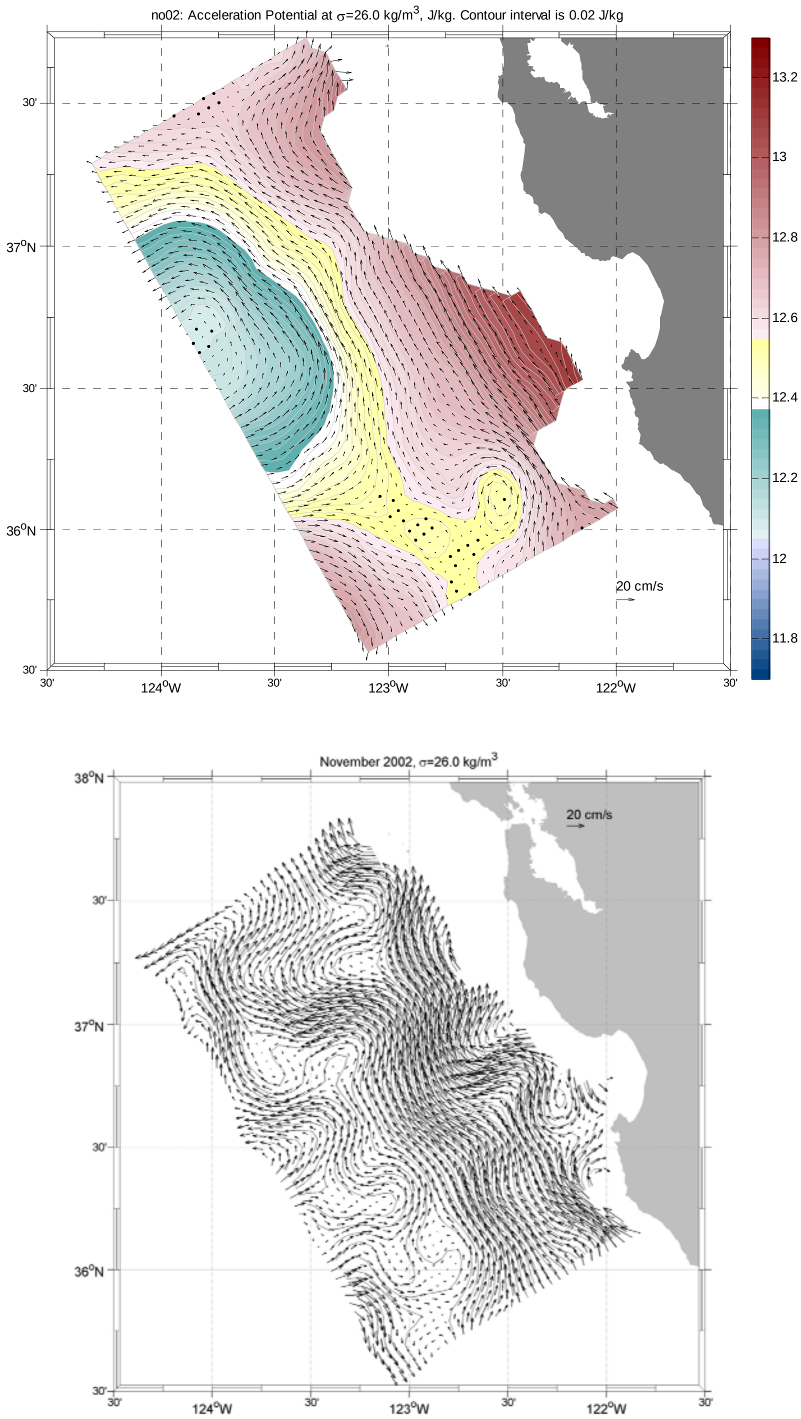


Figure 80. Acceleration potential in J/kg during November 2002 (upper) and ADCP velocities in cm/s (lower) for the 26.0 kg/m^3 density surface. Contour interval is 0.02 J/kg (upper) and the magnitude of flow is given by the arrow shown in the upper right corner (lower).

Acceleration potential on the 26.8 kg/m^3 isopycnal shows northward flow inshore (Figure 81). This corresponded to the poleward flowing California Undercurrent. Since flow was also poleward near the coast on the 26.0 kg/m^3 isopycnal, shoaling of the California Undercurrent occurred.

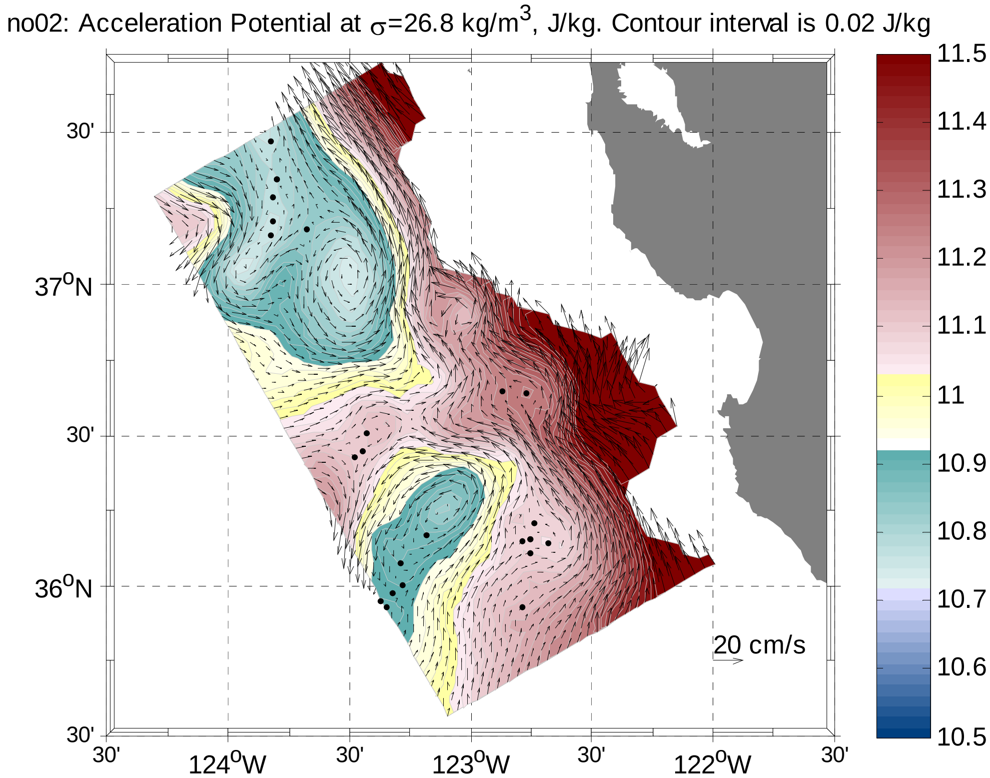


Figure 81. Acceleration potential in J/kg during November 2002 on the 26.8 kg/m^3 density surface. Contour interval is 0.02 J/kg

5. Sea Surface Height – Geopotential and SSHA

The maximum of geopotential (~13.8 J/kg) occurred on the southern edge of the survey area, and extended northward through the region along 123°W (Figure 82, upper). Note that this was similar to MSLA for 14 November 2002 (Figure 82, lower). Isosteres of geopotential were oriented so that flow appears to be poleward through the center of the survey area. There is an area of minimum geopotential (~12.7 J/kg) near 36°45′N, 123°45´W, where flows appeared to be cyclonic; this feature was also seen in MSLA. The range of observed MSLA, ~12 cm, was similar to the observed range of geopotential, 1.1 J/kg.

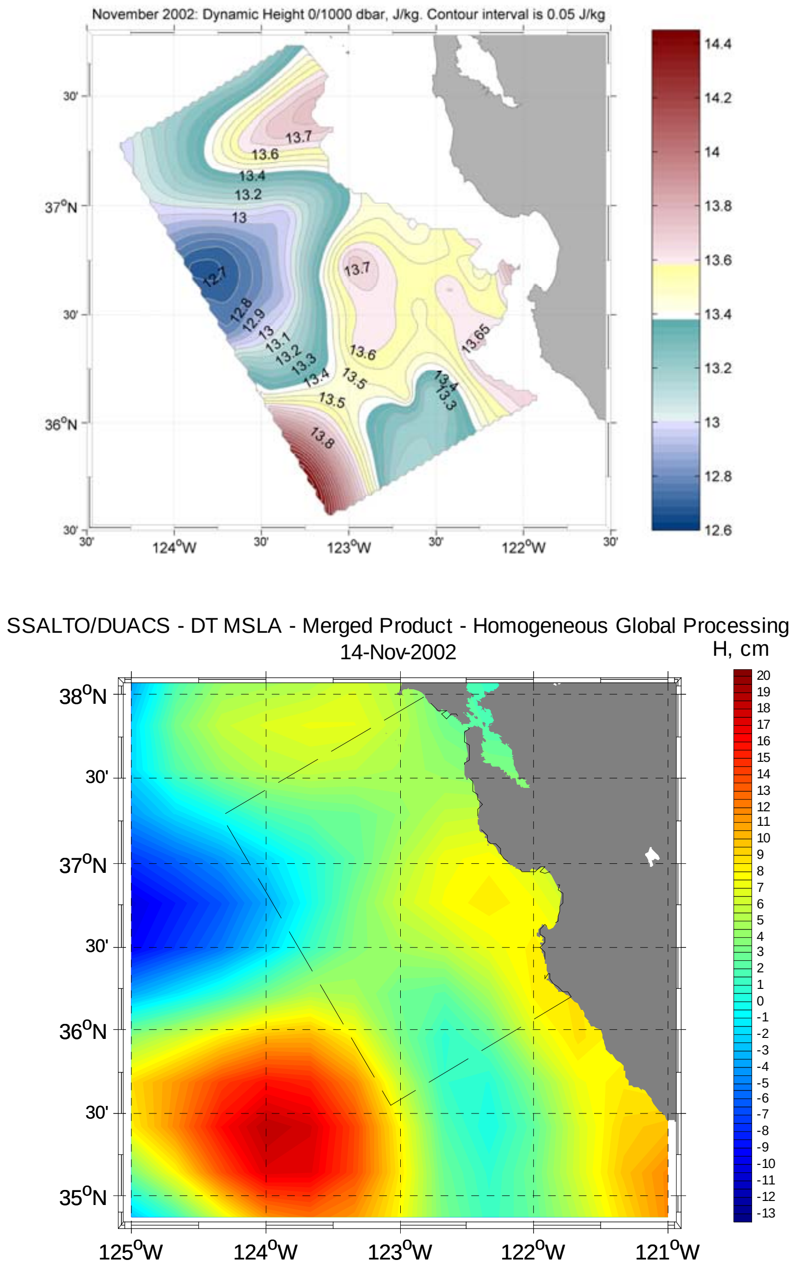


Figure 82. Geopotential (Dynamic Height) in J/kg for November 2002 from 0–1000 dbar (upper) and SSHA in cm (daily mean from 05 December). Contour interval is 0.05 J/kg. (upper) and 0.5 cm (lower).

V. SUMMARY AND CONCLUSION

Subsequent to the large scale analysis of the CCS using CalCOFI data (Lynn and Simpson, 1987), there have been limited opportunities to study variability off Central California using a CalCOFI-type grid of stations. The need to provide modern oceanographic data bases for local U.S. Navy activities provided systematic observations of Central California waters. Ten cruises were carried out on UNOLS vessels *R/V New Horizon* and *R/V Point Sur* between February 1997 and November 2002. Observations extended from Pt. Reyes to south of Point Sur, California to a distance of about 150 km from shore and to a depth of 1000 m where water depth permitted. This thesis has examined results of each of these surveys using T/S diagrams, water properties on a shallow and intermediate depth density surface, and sea surface topography using both satellite altimetry and geopotential, the latter referenced to 1000 dbar.

Mean fields and their variability were described in Chapter III. The deeper 26.8 kg/m^3 isopycnal shoaled offshore, forming a ridge about 100 km from shore that divided low offshore and high inshore spiciness. From the ridge, the 26.8 kg/m^3 isopycnal sloped downward, both toward the coast and offshore. The downward slope toward the coast marked poleward flow in the California Undercurrent (CU); the downward gradient of the slope was greatest within about 40 km of the coast and marked the core of the CU. Water properties on the 26.8 kg/m^3 isopycnal indicated a meridional boundary at about 123.2°W which corresponded to 0 kg/m^3 spiciness; mean fields and individual surveys indicated that filaments or boluses of low spiciness water extended shoreward.

The shallow 26.0 kg/m^3 isopycnal looked like the eastern boundary of a subtropical gyre, sloping upward toward the coast. At the coast, the shallowest pressures, ~85 dbar, corresponded to regions of strong upwelling, e.g., around Pt. Sur, in the coastal region immediately north of Monterey Bay, and offshore of the Farallones Islands. The acceleration potential indicated a shallow ridge, about 0.2 J/kg, extending northwestward across the southern portion of the survey region; this ridge divided onshore geostrophic flow to the north of the ridge from offshore geostrophic flow to the south of the ridge. Next to the coast, the mean acceleration potential indicated poleward flow. On the 26.0 kg/m^3 isopycnal, the regions of higher spiciness along the coast corresponded to upwelled waters; as for the 26.8 kg/m^3 isopycnal, the strongest gradient of spiciness between inshore and offshore waters fell along a meridian, about 123.2°W.

At the sea surface, charts of sea surface anomaly and steric height shared a pattern along the offshore edge of the survey region: ridges to the north and south which were separated by a trough. The southern ridge was better defined as it corresponded to a 5 cm difference in elevation in both mean steric height and the mean SSHA charts for the cruise dates (the corresponding feature in the mean for the weekly SSHA time series was about 2 cm in elevation). Note that the steric height decreased from the coast, corresponding to equatorward flow, and that the gradients were strongest (corresponding to the largest southward flow) along the southwest corner of the survey region.

Analysis of data from individual cruises provided details on the variability of the features described above. The most robust properties were the spiciness distributions. On both the deep and shallow isopycnals, a distinct gradient of spiciness occurred near 123°12´W, separating high spiciness inshore water from lower spiciness offshore. The boundary was most distinct on the 26.8 kg/m^3 isopycnal where this boundary was marked by 0 kg/m^3 spiciness. For the 26.0 kg/m^3 isopycnal, the boundary varied somewhat, but was marked by 0.2 kg/m^3 spiciness.

The property that proved most difficult to analyze were the ADCP velocity data that were mapped onto the 26.0 kg/m^3 isopycnal. Although poleward flow typically occurred along the coast, the fields were dominated by eddies that did not correspond well in either position or rotation to “geostrophic” flows due to pressure change or acceleration potential. While the ADCP data were noisier than integral quantities such as acceleration potential, additional work is needed to understand how these velocity data can be smoothed to yield scales similar to those shown for other fields.

As noted above, the mean pressure field indicated the shallow 26.0 kg/m^3 density isopycnal shoaled toward the coast. The mean picture resembled conditions in February

1997, May 1998, November 1998 and May 2001. In September 1997, November 1999, September 2000, December 2001, and November 2002, the pressure ridge was oriented somewhat east to west through the survey region; while the latitude of the ridge varied, in September 2000, December 2001, and November 2002, it was located near 36°30′N. Finally, in January 1999, the lowest pressures were seen about 50 km from shore (evidence of shallow poleward flow along the coast). Note that the 26.0 kg/m^3 isopycnal intersected the sea surface inshore during upwelling months.

Mean acceleration potential on the 26.0 kg/m^3 isopycnal showed persistent poleward inshore flow for all cruises but with a weak ridge linking high acceleration potential regions near Monterey Bay with an offshore area having similar acceleration potential to the west. Acceleration potentials varied greatly from cruise to cruise. Largest acceleration potentials occurred next to the coast in February 1997, November 1999, September 2000, and November 2002. A trough occurred in the middle of the survey area in September 1997, in part associated with cyclonic circulation to the west of Monterey Bay. Pressure was largest along the offshore boundary of the survey area in May 1998 and was largest in the northern half of the survey region in November 1998 and December 2001. May 2001 was associated with a ridge-trough-ridge-trough pattern from south to north. Finally, January 1999 strongly resembled the mean.

Mean acceleration potential on the 26.8 kg/m^3 isopycnal were similar in pattern to those on the 26.0 kg/m^3 isopycnal except that the offshore maximum of geopotential was weaker at depth. The acceleration potential for each cruise was at a maximum at the coast, reflecting poleward flow of the CU. Differences existed offshore where troughs occurred, corresponding to pressure ridges and cyclonic flows. In November 1998, January 1998, September 2000, December 2001, and November 2002, two distinct offshore regions of cyclonic flow were seen, each with onshore (offshore) flow to its south (north), exchanging offshore and inshore waters. In May 2001, only one large cyclonic region existed in the northern portion of the survey region and in November 1999 the offshore trough extended throughout the offshore region.

Observed patterns of steric height relative to 1000 dbar were similar to those produced by satellite altimeters. This was true despite the fact that the altimetry data reflect 100-km scale variability compared to the 50 km used for objective analysis of hydrographic data. One big difference in the data sets was that the altimeter data indicated weak surface poleward flow along the coast while the steric heights indicated equatorward surface flow inshore. The sea surface height anomalies (SSHA) from AVISO altimetry also had larger values inshore indicating poleward flow, a transition zone, and equatorward flow offshore (as expected for the CCS). A continuous time series of weekly data for the five year period showed a much smaller range of anomalies compared to the individual cruise data. During February 1997, steric heights from cruise data had a larger positive anomaly in the north and west when compared to both the continuous time mean and the central cruise day mean. In September 1997, the SSHA anomaly was completely positive in the survey area when both means contained negative anomalies. In May 1998, the SSHA showed a negative to positive gradient from east to west, opposite of both of the means. For November 1998, SSHA showed a positive anomaly in the south and negative in the north, opposite of both means. In November 1999, SSHA showed an increasing gradient moving towards the western edge of the survey, where there is a decreasing gradient on the mean figures. In May 2001, the SSHA was completely negative, where the continuous mean had a positive anomaly in the northern part.

There were two limitations of the surveys reported here. First, smaller research vessels were used for these surveys which meant that operations were often not possible during periods of stronger winds or higher seas/swell. During such conditions, the ship would move inshore and observe tidal currents in shallow water on the shelf. While these shelf data were important for project goals, they meant that the data from the spatial survey was less synoptic. Second, the cruises were scheduled during periods when the ships would have otherwise been idle, e.g., when strong, steady equatorward winds occurred during the spring upwelling season or the late fall or winter when storms were common. Conditions were not observed in June, July or August.

In terms of data analysis products, it was disappointing that the vessel mounted ADCP data did not provide better agreement with acceleration potentials. The newer models of ADCP and GPS that are currently in use in the academic and survey fleets would certainly have provided not only better data but velocity observations for the deeper density surface.

The research conducted here provided an improved understanding of oceanographic conditions off the central California coast from the surface to intermediate depths. The data analyzed here provides information that can be added to current and future data bases useful for Navy operations involving surface and sub-surface craft as well as unmanned underwater vehicles, and in oceanographic forecasting. The methods used here can be applied to future naval surveys.

A good way to try to provide additional physical understanding of coastal conditions along Central California would be to assimilate these data into numerical models of coastal ocean circulation. Improved models have been developed that can accommodate the complex bathymetry found in most coastal regions, synoptic winds needed to drive these ocean models are provided either by numerical weather models or satellite wind observations, and satellite altimeters can provide continuous constraints on the shape of the ocean surface. Particular features that are difficult to explain are the cyclonic patterns of recirculation of Subarctic waters, the meridional pattern of spiciness, and the lack of interaction between the coastal poleward flows and Monterey Bay.

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF REFERENCES

Aviso User Service, cited 2012: Website used to obtain satellite altimetry data. [http://www.aviso.oceanobs.com/en/home.html].

Carter, E.F., and A. R. Robinson, 1987: Analysis models for the estimation of oceanic fields. *J. Atm. Ocn. Tech.,* **4,** *49–74.*

California Cooperative Oceanic Fisheries Investigations: Official CalCOFI website describing protocols and station grids. [http://www.calcofi.org/.html]

Flament, P., 2002: A state variable for characterizing water masses and their diffusive stability: spiciness. *Prog. in Ocn.*, **54**, 493–501.

Fofonoff, N.P., 1985: A new salinity scale and equation of state for seawater. *J. Geophys. Res.,* ***90,*** 3320–3342.

Huang, R.X. and B. Qui, 1994: Three-dimensional structure of the wind-driven circulation in the subtropical north pacific. *Journ. Phys. Ocn.,* **24,** 1608–1622.

JPOTS editorial panel. *Processing of Oceanographic Station Data*, 138 pp.

Lynn, R.J., K.A. Bliss, and L.E. Elber, 1982: Vertical and horizontal distributions of seasonal mean temperature, salinity, sigma-t, stability, dynamic height, oxygen, and oxygen saturation in the California Current. *Cal. Coop. Ocn. Fish. Inves. Atl.,* ***30,*** 513 pp.

Lynn, R.J. and J.J Simpson, 1987: The California current system: the seasonal variability of its physical characteristics. *J. Geophys. Res.*, **92,** 12947–12966.

Montgomery, R.B., 1937: A suggested method for representing gradient flow in isentropic surfaces. *Bull. Amer. Met. Soc.,* **18,** 210–212.

Montgomery, R.B. and E.D. Stroup, 1962: Equatorial waters and currents at 150°W in July-August 1952. *Johns Hopkins Oceanography Studies,* **1,** 68 pp.

Munk, W., 1980: Internal waves and small scale processes. *Evolution of Physical Oceanography,* B.A. Warren and C. Wunsch, MIT Press, 264–291.

O'Malley, C.M., 2003: The Fall Transition off Central California in 2002. M.S. thesis, Naval Postgraduate School. 82 pp.

Stommel, H., 1962: On the cause of the temperature-salinity curve in the ocean. *Proceed. Natl. Acad. Scien. USA*, **48,** 764–766.

Sverdrup, H. U. and R. H. Fleming, 1941: The waters off the coast of southern California, March to July, 1937. *Scripps Inst. Ocn. Bull.*, **4,** 261–378.

University of Hawaii Department of Oceanography, cited 2012:Guidelines for VMADCP data processing. [Available online at http://currents.soest.hawaii.edu/docs/adcp_doc/index.html]

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, VA

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, CA

3. Dr. Curtis A Collins
   Department of Oceanography, OC/Co
   Naval Postgraduate School
   Monterey, CA

4. Tetyana Margolina
   Department of Oceanography, OC/Co
   Naval Postgraduate School
   Monterey, CA

5. Mr. and Mrs. Ronald Penrose
   1605 Blue Spruce Rd.
   Reno, NV

6. Thomas Rago
   Department of Oceanography, OC/Rg
   Monterey, CA

7. Library
   Moss Landing Marine Laboratories
   Moss Landing, CA

8. Dennis Krynen
   Naval Oceanographic Office
   Stennis Space Center, MS

9. Carl Szczechowski
   Naval Oceanographic Office
   Stennis Space Center, MS

10. Toby Garfield
    San Francisco State University
    San Francisco, CA